TECHNICAL SERVICE CENTER

Denver, Colorado

Dam Safety Risk Analysis Methodology

U.S. Department of the Interior

Bureau of Reclamation

VERSION 3.3.1

May 2003

RECLAMATION'S MISSION

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

DEPARTMENT OF THE INTERIOR'S MISSION

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering wise use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. Administration.

This draft methodology was prepared by John Cyganiewicz, Karl Dise, Dave Hinchliff, Dave Mayer, and Bruce Muller; and Peer Review was by Bill Engemoen and Gregg Scott.

Acknowledgments

Numerous individuals provided valuable input into the creation of this methodology for performing risk analyses in the dam safety program. The authors acknowledge the efforts, direction, and reviews provided by the following individuals that were critical in the completion of this document.

> Dave Achterberg, Jon Ake, Martin Chavira, Paula Engels, Dave Eubank, Wayne Graham, Chuck Hennig, Perry Hensley, Jim Mumford, Chuck Redlinger, Rob Rocklin, John Smart, Bob Swain, Rich Throner, Steve Vick, and Larry Von Thun

In addition, numerous teams within the Technical Service Center “allowed” their projects to be test cases for the development of this methodology. Their cooperation is appreciated.

DRAFT RISK ANALYSIS METHODOLOGY
CONTENTS

I. Introduction

Each and every day Reclamation decides to operate a facility, it is implicitly accepting the risks posed by the structure. By using risk analysis techniques Reclamation is attempting to understand the nature and severity of the risks so that it can make informed decisions. Tightening budget constraints suggest it is appropriate to use risk determinations as a tool to direct funding to those issues presenting the greatest risks. Thus it is imperative that each facility's risk be identified and analyzed to provide correct information to the dam safety decision process.

This document is mostly about risk analysis, that is, how to identify loading conditions, potential failure modes, and consequences, and how to estimate the probabilities for each event. Questions like "does the identified risk justify further action" or "what should be done to reduce risk" belong to risk assessment, and are beyond the scope of this document. While the primary topic is risk analysis, this document starts by providing a brief introduction to risk assessment and risk management concepts. This is so that the reader can understand where risk analysis fits into the entire dam safety process, what the legislative mandate for risk analysis is, and what are some of the appropriate uses for risk analysis. After this brief introduction, the remainder of the document will discuss how to prepare for a risk analysis, how to conduct a risk analysis, and how to report the findings from a risk analysis.

A. Role of Risk Analysis and Assessment in the Dam Safety Program

Risk and uncertainty are intrinsic in water resource management activities. Uncertainty arises from the lack of information about the loads that a dam will actually experience, the lack of perfect information about the manner in which the dam will respond to those loads, and limited information about what the resulting consequences would be. Risk arises from undesirable consequences and the uncertainty over whether or not those consequences will actually occur. Risk analysis and risk assessment should not be confused with risk taking. Contrary to risk taking, risk analysis and assessment provides a method to better manage risks with available resources. Estimating the probability and magnitude of consequences of potential options facilitates decisions that focus available funds where the greatest risk reduction and benefit can be attained. Figure 1 portrays a simple model of how dam safety issues proceed from identification to risk analysis to risk assessment and decision making.

RISK ANALYSIS/RISK ASSESSMENT PROCESS

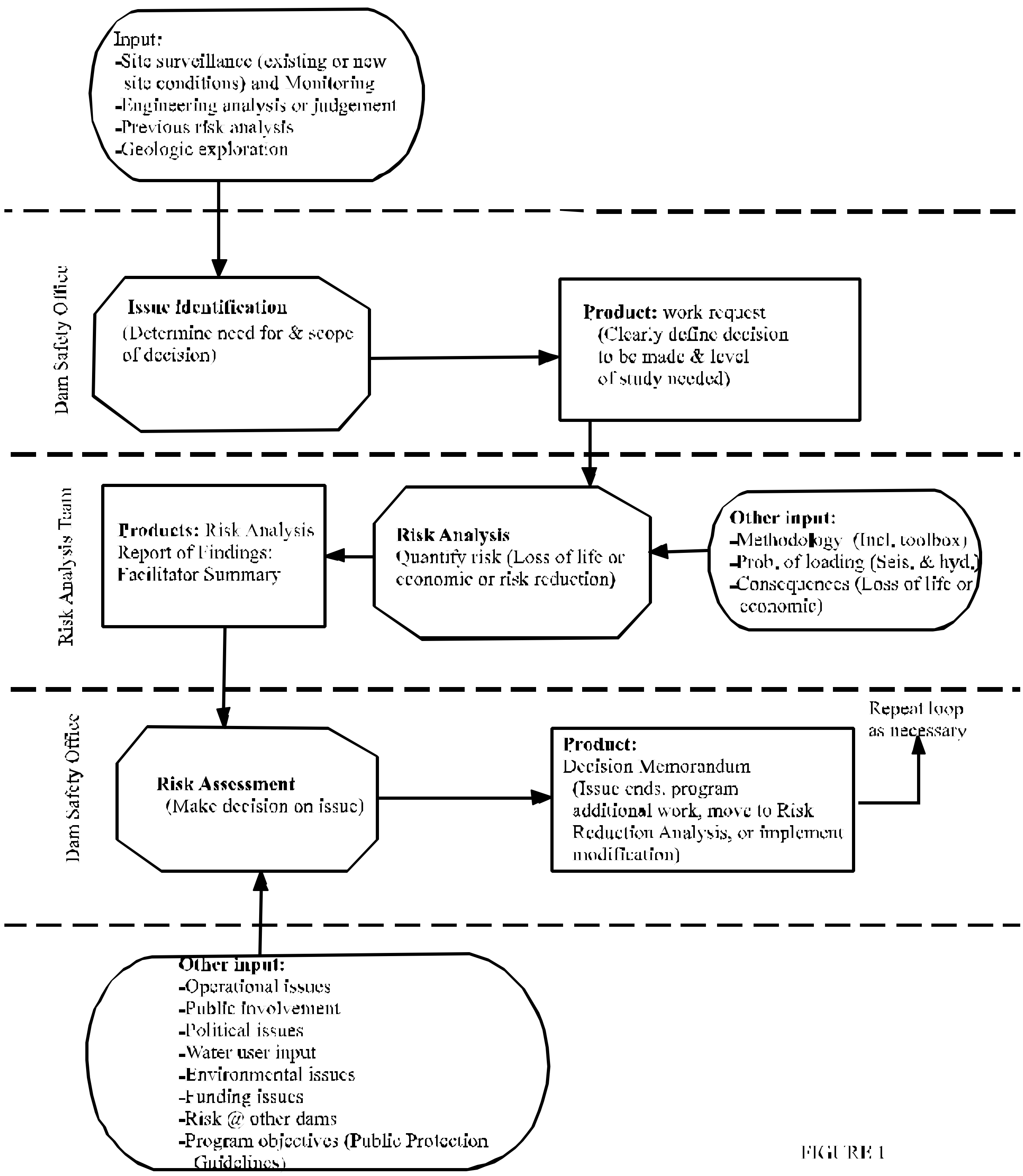


FIGURE 1

The objective of Reclamation's Dam Safety Program is to ensure that Reclamation water impounding structures do not create unacceptable risks to public safety and welfare, property, the environment, or cultural resources. This objective is aimed at fulfilling the Federal Government's trust responsibilities for the safety and welfare of the downstream public. The authorizing legislation for the dam safety program [1] states:

> *"In order to preserve the structural safety of Bureau of Reclamation dams and related facilities, the Secretary of the Interior is authorized to perform such modifications as he determines to be reasonably required."*

Responding to the congressional mandate, Reclamation has refined the goal as follows [2]:

> *"The objective of the Safety of Dams Program is to ensure that Reclamation structures do not present unacceptable risks to public safety, property, and welfare. This requires identifying structures which pose unacceptable risks and taking corrective actions to reduce or eliminate these risks in an efficient and cost effective manner. Reclamation policy is to provide safe structures, but this does not imply a risk free environment. A safe dam is one which performs its intended functions without imposing unacceptable risks to the public by its presence."*

Risk analysis procedures help organize engineering approaches to credibly identify potential failure modes and related downstream consequences which are often the fundamental information necessary to make decisions related to program objectives. However, risk analysis should only be viewed as one of the inputs to the overall risk assessment and decision process. Other typical inputs to the assessment process are traditional engineering analyses and judgements, funding considerations, environmental considerations, public involvement, political considerations and economic considerations. Thus the quantitative and qualitative results of a risk analysis must be melded with the quantitative and qualitative information from these other inputs to form the final decision.

While describing the process of determining unacceptable risks is beyond the scope of this document, additional information may be found in the Reclamation's *Policy and Procedures for Dam Safety Modification Decisionmaking* [2]*; Guidelines for Achieving Public Protection in Dam Safety Decision Making* [3]*;* and *Policy for Decisions Related to Dam Safety Issues* [4].

B. Meaning of Risk and Probability

Among the many concepts proposed for defining risk, the meaning adopted here is most succinctly expressed by Webster's Dictionary as *"the possibility of loss."* This risk definition incorporates the dual concepts of uncertainty about the occurrence of some event (possibility), and the adverse consequences should it occur (loss). In a dam safety context, the event of interest is an uncontrolled release of the reservoir and the resulting consequences which may include loss of life, economic loss, or other adverse consequences. As implied in the definition, there is uncertainty in predicting the future performance of the dam, including the loading conditions it may experience, its response to these loads, and estimating failure consequences. Such uncertainties are inevitable to varying degrees in any risk analysis because of imperfect knowledge or incomplete information about the physical processes involved.

Quantitative estimates of dam failure risk require quantifying the likelihood of loads, adverse responses given the load, and adverse consequences given a failure occurs as well as the uncertainties associated with each. The estimation process relies on engineering techniques whose applications differ little in principle from deterministic dam safety assessments. The difference in a risk analysis is the requirement for quantifying uncertainties in all of their various forms. Probabilistic methods inherently address these uncertainties.

In this sense, probability is a quantified statement of likelihood based on one's degree of belief or level of confidence in the occurrence of a certain outcome, a certain response, or the presence of a certain condition. In most cases the probability of occurrence is not determined solely on the basis of data, analysis or performance. While the estimation of the probability of occurrence can consider such information, there are typically other factors that also impact the estimate. Such factors would include those issues that cannot be quantified or that are statistically verifiable. The probability estimates for all aspects of the problem depend on the state of knowledge at the time of their assessment and the ability of the assessor to express all of the contributing factors and uncertainties as fairly and honestly as possible. In this respect, probability and hence risk itself, are best viewed as the quantified expression of engineering judgment.

At its most fundamental level, the concept of risk analysis embodies identifying and quantifying three elements: (1) the events and conditions that could cause failure, (2) their likelihood, and (3) their consequences. Or more simply put:

- How could failure occur?
- How likely is it?
- What would happen if it did?

Answering these questions provides the data necessary to estimate a quantitative measure of risk as computed by the following equation:

Risk = P[load] x P[Adverse Response given the load] x Adverse Consequence given the failure

C. Intended Audience

This document presents a general approach for analyzing the risk posed by dams. It is intended that this analysis, along with other input, be used by decision makers within the Bureau of Reclamation concerning dam safety.

Within Reclamation, this document is intended to benefit a broad cross section of the staff. Facilitators can use the methods outlined as a road map for guiding risk analysis teams through the process of estimating and documenting risks. Risk analysis participants may use the document to learn how to follow the process. Dam safety decision makers may wish to use the document to gain some background on the methods used to develop the risk analysis results which are being presented to them. The intent during the development of the document was to focus on the facilitators' needs while providing sufficient detail to be educationally valuable to others.

D. Developmental Nature of the Methodology

This document presents methods which are considered to be most reasonable for meeting the objectives of the Dam Safety Program at the present time. As the application of risk based methods in water resources management (and more specifically in Dam Safety) spreads, there will undoubtedly be improved methods developed. When these new methods and supporting toolboxes are developed for Reclamation, this document will be revised to include them.

There will also be specific situations arise which are not adequately addressed by the methods presented in this document. In these cases, risk analysis teams and facilitators are encouraged to:

- Seek out examples of similar situations at other dams
- Seek advice from other employees and/or consultants
- Propose/develop workable solutions which are consistent with the principles of the methods provided in this document.

When these actions result in additional methods or insights which would have benefit to other risk analyses, they will be included in subsequent revisions of this document.

II. Purposes of Risk Analysis

The broad purpose of risk analysis as a dam safety tool is to improve the effectiveness and efficiency of Reclamation's dam safety efforts. However, it is important to recognize that risk analysis, while key to decision making, does not alone constitute a dam safety decision. A number of factors, many external to the analysis, are incorporated and synthesized at the decision making level. The value of risk analysis is derived nearly equally from: 1) the process itself that helps develop a deeper understanding of the dam and the key dam safety issues, and 2) the numerical results that are used in the decision making process, especially for setting priorities. The following discussions describe the various goals that risk analysis should seek to achieve.

A. Communicating Risk

A primary purpose of the risk analysis is to communicate risk judgments, both to the decision maker and within the study team itself. Whereas a deterministic dam safety assessment can identify potential dam safety deficiencies, communicating the associated risks enhances information content by expressing judgments about the relative severity and importance of the risks. Quantified risk analysis results provide a common denominator for comparing conditions that could not otherwise be related to each other (for example, post-liquefaction FS = 0.9 versus 80% PMF spillway capacity), both for a given dam and among different dams.

If risk analyses are to serve the decision maker in this way, the risk must be communicated clearly and unambiguously, and the various sources of risk for a given dam must be explicitly identified. It is not sufficient to determine the total risk associated with a dam without also explaining the underlying rationale for why the value resulted and how it was derived. This includes the identification of the major sources of risk (loading conditions and failure modes). The logic structure contained in the event tree generated as part of a risk analysis can be a significant aid to this end if it is constructed with appropriate logic and clarity of communication in mind, as discussed subsequently in Section IV.B (Developing Event Trees). In addition, any risk analysis will itself be subject to uncertainty arising from different interpretations of the information available. The risk communicated to the decision maker needs to be accompanied by some statement of the confidence to be placed on it, and various means for doing so are described in Section V.B (Uncertainty Analysis). All of these aspects of risk communication depend heavily on the presentation and completeness of the risk analysis documentation, matters addressed in Section V (Documentation and Presentation).

An equally important aspect of risk analysis is to promote interchange among the team members during the process. Here too, discussions centered on risk provide a focused format for comparing and relating the significance of potential failure modes and processes across the boundaries of the various technical disciplines involved. A sense of scale and proportion to the importance of specific analysis and evaluation efforts emerges as the corresponding risk contributions from these studies are identified. The participation of field personnel as well can be invaluable. Certain site-specific features whose significance might not otherwise be obvious can assume critical importance when viewed in the kinds of risk-related contexts that these interactions provide.

B. Improving Understanding of Dam Behavior

The safety of a dam can most effectively be improved if its design, construction, and behavior are thoroughly understood. Therefore, another primary purpose of risk analysis is to enhance this understanding by more explicitly identifying the features and conditions of the dam that contribute to its vulnerability or robustness. This can come about in several ways.

The process of detailing potential failure modes and the requirements for those failure modes to develop into an uncontrolled release of the reservoir provides a very different perspective on dam behavior than the perspective obtained from a design point of view. When the participants are challenged to find ways in which a dam could fail, they are more likely to identify vulnerabilities. Recognizing such potential vulnerabilities provides a better basis for understanding the manner in which the dam will respond to a variety of loading conditions. By asking "how could this dam fail?" it encourages greater attention to the unique conditions and performance history of each individual structure. The result can be to identify important mechanisms and conditions that might otherwise have been overlooked. A relative sense of urgency associated with the various risk scenarios is also obtained.

The outcome of the risk analysis will provide information that permits comparison of the relative risk contributions of each potential failure mode and the relative risk contributions of each loading increment considered. In relation to the total risk for the dam, this information allows the dominant risk-producing conditions to be identified, which in turn can then serve to focus efforts on the most critical aspects of the project. For example, determining that spillway erosion under 100-year recurrence interval floods would produce significantly greater risk than overtopping under PMF conditions would lead to greater emphasis on the risk of the more frequent, but perhaps less catastrophic erosion problem. Deriving the risk contribution for each potential failure mode promotes a more balanced view by reducing overemphasis on those mechanisms for which advanced analytical methods may be available at the expense of those for which computational techniques are less well-developed or not available.

Seen in this light, risk analysis is a dam safety tool for refining engineering insight.

C. Identifying Information Needs

A further purpose of risk analyses is to provide a road map for guiding any additional dam safety investigations. Logically, those failure modes that produce the largest risk contributions should receive greatest attention. Conversely, further investigations may provide fewer benefits for those failure modes shown to contribute little to total estimated risk.

In some cases where little information is available, confidence limits on the results of the risk analysis may be comparatively wide. If greater refinement is necessary for decision making purposes, information from further investigations or technical analyses may have the potential to narrow these limits if targeted to the more significant risk contributors. On the other hand, additional information unlikely to substantially influence the estimate of risk may not be warranted. "Information" in this context includes not only field exploration data and consequence estimates, but also more readily-obtained information from such sources as construction records, case-history literature, or analyses that may not have been available at the time of the previous risk analysis stage.

Risk analysis should not be seen as discouraging the gathering of information that is critical to understanding the behavior of the dam. Rather, the intent is to use risk as a means for more precisely targeting the areas where further information is most required and pinpoint the types of information of greatest benefit.

D. Formulating Corrective Action Alternatives

When it is necessary to develop alternatives for reducing risk at a particular structure, the information developed in the course of preparing a risk analysis will aid in formulating alternatives which effectively mitigate the risks identified. By understanding the goal of risk reduction, the nature of the risks involved, and the operational needs of the project, a group of effective alternatives can be developed and evaluated. When risk reduction becomes an evaluation criterion along with cost optimization and any other appropriate objectives, the resulting evaluation criteria provide an effective framework for developing alternatives.

By applying the evaluation criteria to brainstorming alternatives, inferior alternatives can be identified and eliminated from further consideration at an early stage. The goal is to eliminate those alternatives which have no reasonable chance of being selected as the alternative to be implemented. For example, an alternative with higher costs and lower risk reduction is inferior to an alternative with lower cost and greater risk reduction when there are no other criteria to be evaluated.

E. Allocating Resources

Reclamation's available resources for studying dam safety issues are finite. Limitations may include availability of key personnel, equipment, funding, and/or time. In each of these cases, choices must be made concerning the priorities for addressing the various risks at Reclamation facilities.

With over 300 dams categorized as high hazard structures, Reclamation is constantly assessing load, response, and consequence data for its inventory of dams. While the assessment may not be in great detail, it provides a general indication of which dams contribute the greatest risks to the public and therefore require additional investigation to better quantify the risks and support decisions of whether or not to make dam safety related modifications to reduce risk at a dam. With so many dams in Reclamation's inventory, it is unlikely that up-to-date documented risk analyses will be available for all dams when resource allocations for dam safety enhancement are necessary. However, it is still prudent to set priorities on the basis of our best knowledge of the potential risk to the public at any given point in time. Prioritization of issues can occur for a given dam (i.e. treat a piping problem but defer the hydrologic investigations) or for a group of dams (i.e. when several dams are situated in the same drainage basin or in the same vicinity).

Since perceived risk is not static over time, risk analysis also provides a basis for revising priorities when the estimated risk to the public changes. Such changes may be the result of changes in the population at risk, changes in our understanding of the loading conditions, changes in reservoir operations, or the development of unexpected behavior in the dam. When changes in the risk parameters occur, the risk analysis should be revisited to determine if the allocation of additional resources for dam safety enhancement is necessary to provide adequate public protection.

III. Preparing for a Risk Analysis

A. Defining Study Objectives

Since a risk analysis can be used beneficially for a variety of purposes, the specific objectives of the risk analysis and questions to be answered should be addressed prior to the risk analysis team meeting (described in Section IV). The scope of the work to be performed, time and budget constraints, and target audience for the risk analysis must be documented such that there are common expectations for the results (and how those results will be used) between those performing the risk analysis and those using the results. As the risk analysis is planned, it is important to ensure that the scope of the work planned results in information which is valuable to the decision makers in Reclamation. Once the plan has been developed, it is important to recognize that unexpected information revealed during the risk analysis can lead to the revision of the study plan and objectives.

1. Risk Analysis Categories. - For the purpose of this methodology as it relates to Reclamation's Dam Safety Risk Management process, there are two basic categories of risk analyses. The first, termed "Baseline Risk Analysis," determines the risk represented by the existing structure as it now stands and how it is currently operated. If there is a decision made that the baseline risk justifies additional action, then a second category of risk analysis may be employed. This second category, termed "Risk Reduction Analysis," determines the potential risk reduction from the baseline condition for various alternatives that might be applicable at the site.

It is important when planning for a Risk Analysis to understand the current status of risk studies for the dam so appropriate comparisons can be made. Performing a Risk Reduction Analysis without having already developed the baseline risk is inappropriate.

The different types of risk analyses for each category are described below.

Baseline Risk Analysis. - There are generally three types of Baseline Risk Analysis used in Reclamation:

- Portfolio Risk Analysis: Within the U. S. Department of the Interior, there is a Technical Priority Ranking (TPR) system in use for Dam Safety. The existing TPR system has been in use for more than a decade to prioritize dams for study or funding. The TPR is established and updated by the Dam Safety Inspector (Examiner) during preparation of the SEED inspection report. Existing information on the dam and observations made during the inspection are used in determining the TPR.

  There are currently ~~some~~ initiatives within the Department to replace the existing TPR with a system that is risk-based. As they are developed and implemented, this portion of this methodology document will be revised as appropriate.

- Comprehensive Facility Review (CFR): Senior Engineers preparing the Report of Findings (ROF) portion of the CFR estimate the risk posed by the existing structure. The results are generally reported in terms of the Tier 1 and Tier 2 guidelines [3] and while typically less refined than the "Issue Evaluation Risk Analysis" described below, the CFR still establishes an approximate baseline risk analysis of the structure. The risk analysis portion of the CFR includes a definition of loading conditions, failure modes, and consequences for all load classes (static, hydrologic, and seismic). Structural failure modes are identified that improve the understanding of the dam's behavior, however, response probabilities and associated uncertainties are typically only considered in a global sense and detailed event trees are usually not prepared. Estimates are generally only prepared by the Senior Engineer and they are peer reviewed by a senior member of the staff. These estimates are based on the experience of the engineer and on the data which is readily available. Uncertainty of the quantitative estimates is generally not considered at this stage but qualitative discussions of uncertainty may be included to help the decision makers when assessing the report.

All the information on the dam that exists at the time the ROF is prepared is used as input to the CFR risk analysis. The Senior Engineer will also consider information gained from the CFR site inspection. Hydrologic and seismic hazard studies are also to be prepared for the CFR process and should be used by the Senior Engineer when performing the risk analysis for the structure.

- Issue Evaluation Risk Analysis: This level of risk analysis is generally the most refined of the baseline risk analyses. The decision makers may decide from the results of the CFR or other recent information that a Issue Evaluation Risk Analysis be commissioned. Once commissioned, the Facilitator(s) and Team Leader would put together a team typically consisting of personnel from the TSC, Area, and Regional Offices. The team may be asked to verify the existing risk by considering existing risk analyses, additional data that may have been obtained since any previous risk analysis were performed, or to consider additional expertise (in the form of the experience of the personnel included in the team) while estimating risk.

  The team estimates risk in terms of Tier 1 and Tier 2 guidelines and will include a portrayal of uncertainty in their estimates.

  This level of risk analysis typically involves developing event trees describing failure modes and estimating structural response probabilities, load probabilities, and consequences. At this stage, the appropriate technical staff becomes involved in the process by sharing their knowledge of the dam and how it will respond to various loads as well as participating in estimating response probabilities. Areas of uncertainty will be identified for consideration by the decision makers during their assessment of the risk. The team should identify data needs where data collection would be expected to significantly improve risk estimates at an economical cost in terms of time and money.

  Over time there may be multiple Issue Evaluation Risk Analyses commissioned to continue to refine the baseline risk as more data is collected, different site information is obtained, other expertise is brought in, or as modifications are made to the structure. The goal is to progress to a baseline risk analysis that is adequate for the decision makers to continue to make assessments of the appropriate response to take for the structure.

Risk Reduction Analysis. - A Risk Reduction Analysis is an analysis that examines alternatives as to their impact on the baseline risk. This category of analysis is begun once the baseline risk indicates corrective action is necessary.

- Alternative Identification Analysis - At this level of analysis, the goal is to determine what alternatives would potentially reduce the risk to acceptable levels so that further design concepts and cost estimates can be developed. While a team approach is typically used, the team is small and the process at first is not very detailed. The team would examine the baseline risk for the components that are producing the highest risk and brainstorm alternatives that would have a good chance of economically reducing risk to acceptable levels. Alternatives could be both structural and non-structural and should consider all the components of the risk. The risk reduction may not be actually quantified but at a minimum the key concepts of where risk reduction is anticipated should be reported.

- Alternative Evaluation Analysis - At this level of analysis the goal is to fully examine alternatives for their ability to reduce risk. The team should use all previous analyses and information to estimate the potential risk reduction of the alternatives. If alternatives include structural modifications, a certain level of design detail will be needed to make the estimates such that the strengths and weaknesses of the proposed modifications can be studied. Costs of the alternatives may be needed if there is a need to quantify the economic risk reduction or if risk reduction indices [3] are to used by the decision makers. Previously developed event trees can be revised to study and quantify the effects of the alternatives on the components of risk.

Table 1. - SUMMARY OF BASELINE RISK AND RISK REDUCTION ANALYSES

Category	Type	Product(s)	Staffing	Duration	Methods Used	Data Used
Baseline Risk Analysis	Portfolio	TPR	Examiner	few hours	Prescripted	- available data - field observations - known conditions
	CFR	ROF	Senior Engineer	1-2 days	- historical failure probability - simple event trees - back calculation to Tier 1 & 2	- above data - experience of Senior Engineer - hydrologic & seismic hazard study
	Issue Evaluation	ROF	Team	1-10 days for meeting 1-20 days for documentation	- detailed event trees - decomposition to estimate response probabilities	- above data - new data - experience of team members
Risk Reduction Analysis	Alternative identification	- ROF - FER - Service agreement	Team	1-10 days for meeting 1-10 days for documentation	Brainstorming based on baseline risk	Results of Project team baseline risk analysis
	Alternative evaluation	ROF	Team	1-10 days for meeting 1-10 days for documentation	Revise event trees for each alternative	Field data; designs; and cost estimates

2. Documenting the Scope of Work. - The Dam Safety Office, Regional Dam Safety Coordinator, Area Office representatives, and Team Leader define specific risk analysis study objectives, including the basis for any decision to be made and the questions to be answered by the risk analysis study team. The objectives may include an assessment of the risk of loss of life and risk costs, or a determination of areas of concerns that need additional data collection and analysis. The level of effort required for the risk analysis is one of the outcomes of this discussion.

A written scope of work, prepared by the Team Leader, is extremely valuable in defining the effort required for the risk analysis . While the document should have sufficient data to provide a common understanding of the expectations, it can be prepared in a simple format such as the worksheets shown in Figures 3a and 3b. The key elements to be identified include the objectives of the Dam Safety Office, products expected, participants, a schedule and budget, data availability and requirements, and the level of effort required from the participants. When completed, the scope of work should also meet the requirements of Technical Service Center (TSC) Memorandum No. 3, which describes the preparation of service agreements.

The products of a risk analysis will vary with the objectives of the risk analysis. The products can generally be classified as those which provide a description of the baseline risk at the dam and those which frame potential future actions on the impacts to the baseline risk. Products which describe the baseline risk could include event trees, descriptions of potential failure modes, descriptions of loading and exposure conditions, evaluation of existing data and analysis, and charts showing risk and consequences associated with the dam in its present condition. Products which frame future action could include evaluation of additional data which would add value to the analysis of risks, relative ranking of potential risk reduction alternatives with respect to risk, and estimates of the cost effectiveness of potential risk reduction alternatives.

As the plan for the risk analysis is being formulated, it is also important to recognize that there may be key questions from decision makers or others which need to be answered as part of the process. The risk analysis will be of greater value to the decision makers if these questions are identified and documented at the start of the process so that they may be directly addressed. Some examples of the types of questions frequently asked include:

- Which failure modes contribute the greatest risk?
- What uncertainties enter into the estimates of risk?
- What information could be generated to reduce the uncertainty?
- What outcomes could reasonably be expected to result from collecting the information?
- How would the risk be affected by each of these outcomes?
- What are reasonable alternatives for future action and what will they cost?

While not all of these questions need to be answered for all risk analyses (depending on the category), the risk analysis participants need to identify what questions are important to the decision makers and answer those questions through the risk analysis process.

Since risk analyses can be performed to varying degrees of detail, the detail required should be documented at the beginning of the study. Issues to be addressed would include targeted failure modes (if any), the availability of data, and any specific desires of the decision makers regarding format of the results.

Risk Analysis Scope of Work

Dam: ____________________ Date: ____________

Risk Analysis Category: 9 Baseline
9 Identify Risk Reduction Alternatives 9 Evaluate Risk Reduction Alternatives

Dam Safety Office Objectives:

9 Determine whether or not identified dam safety issues require further investigation

9 Identify key sources of risk and uncertainty

9 Identify future data and analyses needed to determine if risk reduction is required

9 Identify alternative courses of action for risk reduction

9 Quantify risk reduction for alternative actions

9 Other ____

Required Products:

9 Risk Analysis Report
9 Draft service agreement for next phase
9 Other __________________________

Risk Analysis Participants: (indicate which team member will serve as the recorder and prepare the report) (not all of these participants may be required)

9 Facilitator(s) ______________________
9 Team Leader ______________________
9 Geotechnical ______________________
9 Structural ______________________
9 Waterways ______________________
9 Geology ______________________
9 @Risk Resource ______________________
9 Region ______________________
9 Area Office ______________________

Risk Analysis Consultants: (Provide data and may participate part time)

Flood Hydrology/Paleoflood ______________________
Seismic Hazards ______________________
Consequences ______________________
Other ______________________

Schedule:

Start	__/__/__	Draft products complete	__/__/__
Data complete	__/__/__	Meeting complete	__/__/__
Products delivered to DSO	__/__/__		

Figure 3a - Worksheet for Risk Analysis Scope of Work

Data Availability:

Data Type	Data Currently Available	Data Required	Date to be Completed
Flood Hydrology			
Paleo Flood(s)			
Seismic Hazard Curves			
Dam Breach Parameters/ Inundation Mapping			
Consequences			
Other			
Other			

Staff-day Estimate:

Code	Data Collection	Risk Analysis	Draft Products	Review	Final Products
D-8110					
D-8130					
D-831_					
D-832_					
D-8330					
D-8530					
D-8540					
Total					

Client Approval: ______________________________ Dam Safety Coordinator ____________ Date

Figure 3b - Worksheet for Risk Analysis Scope of Work (continued)

3. Time and Budget Considerations. - Time and budget constraints play a key role in defining the study objectives. Time, budget, and the scope of the services to be performed are closely related and must be balanced to achieve desired results. A key consideration is whether or not the analysis is allotted a specific budget. If a specific budget and/or time is allotted, the scope of work must be adapted to generate the most valuable risk information within the allotted time and budget. If the time and budget are flexible, the scope of work must be negotiated with the decision makers such that the scope of work will yield the required results in a cost effective manner. When developing a scope of work and associated time and budget estimates, some considerations include:

- Stage of Dam Safety Process - For Baseline Risk Analyses, decision makers may only need information on the need for additional data collection or they may desire more detailed information in later stages of the dam safety process to complete their risk assessments.

- Potential for Adverse Consequences - Risk analyses for major storage dams tend to require greater effort than small dams with small reservoirs. In addition, dams with large downstream populations may require more attention than those with small downstream populations.

- Public Awareness - Risk analyses for dams with higher degrees of public scrutiny may require the same effort to reach problem understanding as other dams, but will likely require greater attention to presentation and documentation of the risks associated with alternatives than those with lesser public concern.

By addressing these considerations in combination with developing an acceptable scope of work, an appropriate schedule and budget can be developed for the risk analysis.

4. Target Audience. - The target audience of every risk analysis is the group of decision makers who must determine what future actions, if any, are required with respect to the safety of the dam. In accordance with *Policy for Decisions Related to Dam Safety Issues* [4], this group generally consists of the Regional Director, Area Office Manager, and Chief of the Dam Safety Office, or their representatives. The objectives of the risk analysis should ensure that concise and adequate information concerning risks and consequences is provided to these individuals for their evaluation. In defining the objectives of the risk analysis, participants in the process must understand that their role is focused on providing risk based information rather than making the decision.

While the primary audience of the risk analysis is decision makers, there are likely to be other audiences which derive benefits. These groups may include the risk analysis participants who gain a better understanding of the performance of a dam, operations or water district personnel who gain a better understanding of how their operations decisions impact the risk to the public, and program managers who may use the risk analysis for prioritizing future work. While each of these groups has a valid interest in the risk analysis process and results, it is important to ensure that the focus of the risk analysis is maintained on providing the decision makers with information that contributes to their decisions.

5. Approval. - The final step of defining the risk analysis objectives is to obtain approval from the Dam Safety Office. This part of the process is complete when there is agreement on the scope of work, schedule, estimated cost, and intermediate checkpoints. While there can be some effort involved in reaching this agreement and approval, it is generally helpful in ensuring that all participants have a clear understanding of the expected outcomes of the risk analysis.

B. Establishing the Study Participants

1. Composition. - Participants in the risk analysis depend on the type and complexity of risk analysis being conducted. It is difficult to define a generic list of participants that could conduct all types of risk analyses. The composition of the team will depend on the objectives of the analysis and on the level of detail expected.

For the Baseline Risk Analysis in the CFR process, a senior engineer typically prepares the risk analysis and a peer reviewer provides the technical review of their analysis. Since the purpose of the analysis is usually to identify and prioritize dam safety issues in need of additional attention, the senior engineer needs a strong familiarity with risk analysis procedures and failure mechanisms at the dam. The engineer usually has many years of experience evaluating dam safety deficiencies, but should not hesitate to draw upon other technical specialists as needed to address other areas of expertise.

For an Issue Evaluation Baseline Risk Analysis, the participants usually consist of a facilitator(s), recorder or note-taker, team leader, and a various number of team members and technical specialists (including someone to operate the software to manage the information generated - currently @Risk and Precision Tree). The technical specialists participate on an as-needed basis to understand and guide the thought process of the team and to provide specialized information needed for the analysis.

2. Group Size and Organization. - Selection of the risk analysis participants is an important step in preparing for a risk analyses. The number of participants requires balancing inclusiveness and diversity against group effectiveness and cost. Potential participants include technical staff familiar with the dam; operations personnel; technical specialists familiar with loading conditions (loading specialists), failure consequences, or dam safety issues; Regional and/or Area Office dam safety coordinators; Dam Safety Office program managers; outside experts; and others who may be able to assist in assessing the critical safety issues for the dam. To keep the process as efficient and effective as possible, participants may need to function in more than one role, as long as they are qualified for each role. For example, the team leader may also serve as the author of the risk analysis report, or a technical specialist may function as the recorder.

For an Issue Evaluation Baseline Risk Analysis, participation by regional and area office personnel is generally very beneficial since they generally have a good understanding of the local conditions and dam operations. For a Risk Reduction Analysis, some of the same individuals may have important contributions in the analysis of alternatives. Area Office and Regional Personnel may also participate in a risk analysis to gain knowledge of the analysis so that their job of disseminating the information to the public is made easier.

The size of the risk analysis team and how it is organized are integrally related. While there are few rigid rules for either, some general guidance can be offered.

C Ordinarily, most risk analyses will consider seismic, hydrologic, and static failure modes, supported by individual technical specialists in these areas. It is useful to conduct an introductory session with all team members in attendance during which basic information about the dam and downstream consequences are reviewed, and the study objectives are established. It is also desirable for all participants to assist in identifying loading conditions, failure modes, and consequence scenarios. This provides a common basis for understanding and sets the stage for the task ahead. Similarly, a closing session with all team members is important for communicating and synthesizing the outcome of the analysis, establishing consensus on the meaning of its results, pointing the way toward identifying data needs, formulating corrective alternatives, and achieving several of the other purposes outlined previously in Section II.

- For an Issue Evaluation Baseline Risk Analysis during which event trees are prepared and probabilities assigned, it can be useful to convene separate subgroups for the seismic, hydrologic, and static aspects. If subgroups are established, it is important that there be a core group of participants that are active in all subgroups in order to ensure consistent treatment of information between groups. For any one of these subgroups (seismic, hydrologic, or static), the following numbers of participants are generally considered, though not all are necessarily required:

Participant	Number	Role
Facilitators	1-2	leads discussion (full-time)
Team Leader	1	overall coordination, ensures consistency (full-time)
Recorder	1	compiles information for documentation (full-time)
Technical specialists	1 - 2	provides seismic, hydrologic, or static response input (full-time, may be an identified participant in the risk analysis or a person with specialized knowledge in the subject matter.)
O&M personnel	1 - 2	provides detailed site information (full-time)
Loading specialists	1 - 2	explains derivation of flood or earthquake recurrence relationships (part-time)
Consequence specialist	1	provides guidance and estimates on downstream consequences
Precision Tree/ @Risk operator	1	assists participants with capturing and displaying event trees and probabilities so that failure modes and risks can be understood real-time (full-time)

These numbers seek a balance between the need for a full range of skills in providing information and conducting the analysis on one hand, and the desire to keep the group to a manageable size on the other. In some cases, more than about ten participants can considerably complicate the task of the facilitator(s) in moving the process forward without providing significant perceived benefit in terms of improved input.

3. Roles and Responsibilities. - Every participant has a unique role on the risk analysis team. The team leader is given the task of coordinating and ensuring completion of the risk analysis. Therefore, the team leader's first job is to obtain a trained facilitator or co-facilitators. The facilitator(s) work with the team leader and Dam Safety Office Program Manager to determine the expertise needed and establish the objectives and makeup of the team. One of the goals in establishing the participants is to select people whose qualifications make the process and results credible. The team leader and facilitator(s) should communicate the study objectives and individual roles and responsibilities to the team members at the beginning of the study. They should consult with the technical and loading specialists before the risk analysis to determine what information is available or needed for the risk analysis. The following paragraphs describe the various team members' roles and responsibilities that are typically needed to conduct a risk analysis.

The team leader makes arrangements for obtaining the necessary resources to conduct the risk analysis and is responsible for scheduling and budgeting. The leader's duties include preparing service agreements, establishing meeting times, arranging conference rooms, and communicating the budget and schedule to each team member and the client. The team leader should also collect relevant reading materials and make them available to the team before the first meeting.

The facilitator(s) should thoroughly understand the risk analysis process and have considerable experience leading and participating on risk analysis teams. The team leader relies on the facilitator(s) to provide direction and advice and to draw out ideas and opinions while conducting the risk analysis. Together, they share ownership in the analysis and help each other in keeping within budget and on schedule, while attaining the study objectives. Several key characteristics are needed in a facilitator to assure a successful risk analysis. The facilitator should have participated in several risk analyses as a participant before attempting to facilitate and should have good communication skills. He/she should be able to run an effective meeting and to elicit ideas and opinions in an impartial manner. The facilitator should understand group dynamics to deter strong personalities from dominating the risk analysis and unduly influencing others. The facilitator should also be knowledgeable about dam failure modes and event tree construction, and should have experience in bringing the risk analysis process to closure. The facilitator(s) are responsible for running the meetings, summarizing key points in the discussion, eliciting expert opinion, leading development of the event tree, assisting the participants in interpreting the results, and ensuring the recorder gets the necessary information documented. The facilitator also needs to be adept at recognizing individual biases and take steps to avoid allowing personal agendas to sway the results. The facilitator(s) will run the meeting using the processes as outlined in Section IV.

Responsibility for calculation of final probabilities and development of the event tree should be assigned to the operator of the @Risk software or another participant. Loading specialists have the responsibility to document the justification for loading condition probabilities and consequences.

Risk analysis participants should represent a variety of viewpoints and specialties. The group should be tailored to address the specific questions that have been defined in developing the study objectives. The participants should have extensive experience in their field of expertise and should have considerable project-specific knowledge. Ideally, at least one or more participant should have extensive knowledge of the operation and maintenance of the structure, and usually will come from an Area or Regional Office.

Where a team is conducting a risk analysis, a subgroup of the participants knowledgeable about a certain failure mode or loading condition may be responsible for development of system response probabilities. While these participants are meeting, loading specialists, technical specialists, and other technical staff can be called in, as needed, to supplement their expertise. These specialists might have extensive knowledge about the potential loading conditions, engineering analyses, consequences of dam failure, economics, etc. These experts are encouraged to help the team in estimating system response probabilities.

Specialists are responsible for development of loading conditions and probabilities (e.g., earthquakes, floods) and for development of consequences. Together, the specialists and other participants will develop warning time scenarios for use in consequence evaluations. Other specialists may also be called upon to conduct additional analyses of structural response; provide briefings on specific aspects of response analysis; and assist in determining system response probabilities as required. While briefing the team, the technical specialists must convey an understanding of the assumptions and uncertainties of their analyses to the rest of the team.

4. Recognizing Limitations. - The composition of the study team will generally consist of staff members with varying degrees of knowledge and enthusiasm for the risk analysis process. The facilitator(s) should be aware of potential biases which individuals may have relating to estimating probabilities. Although bias can take many forms as discussed subsequently in Appendix A, one of the more significant is known as motivational bias, when the probability estimator has some stake or interest in the outcome of the analysis. This might occur, for example, if a team member were to attempt to please a superior with a "favorable" outcome, or were to promote the adoption of some particular modification measure, or stood to benefit from adopting certain investigation techniques that the analysis might recommend.

The facilitator(s) needs to be alert to the potential for motivational bias among members of the study team. In unusual cases, such persons might be given the opportunity to be excused from a particular risk analysis, but more typically a candid discussion emphasizing the need for impartial judgments without preconceived outcomes may help to achieve the same end by conveying the facilitator's awareness of these effects. If there is reason to suspect that motivational bias may have substantially influenced the outcome of a risk analysis, the facilitator(s) are obliged to make this known in the documentation and communication of results.

C. Risk Analysis Reading Materials

Participants in the risk analysis need to come to the initial team meeting prepared to discuss project-specific failure modes, loading conditions, operations, and the potential consequences of dam failure. This requires each participant to familiarize themselves with the project and risk analysis procedures before the meeting.

The team leader is responsible for assembling a package of pre-risk analysis reading materials and distributing the information to the team. The purpose of assembling the package of reading materials is to begin to create equal understanding among participants about the risk analysis process and problems at the dam, so that each member can confidently contribute to the analysis. The materials should include project-specific reports and general information describing the methodology for conducting a risk analysis.

If risk analysis participants would like to know more about the overall risk analysis process, general information describing how to conduct a risk analysis is contained in this document. Toolboxes (various methods, processes, and information related to risk analyses) are currently being developed that will enhance the risk analysis process described in this methodology, and these toolboxes will be included with this document as they are completed. Information concerning the manner in which the results of the risk analysis are used is included in *Guidelines for Achieving Public Protection in Dam Safety Decision Making*; Bureau of Reclamation; April 4, 1997. In addition, the participants should have access to any previous risk analysis reports for the dam and/or an example of a recent risk analysis report and case histories of dam incidents/failures for similar facilities.

Project-specific reports and evaluations should also be collected. This material includes field inspection reports, construction and operations histories, as-built drawings, previous dam safety evaluations and analyses, geologic data, seismotectonic reports, flood studies, reservoir routings, performance parameters, early warning system reliability studies, operating criteria, and pertinent correspondence. The SEED Data Books and project files are sources of most of these materials for Reclamation dams. The State Engineer's Office, other Federal agencies, or private owners are possible sources of information for non-Reclamation dams.

IV. The Team Meeting

The information presented in this section was written primarily as a guide for the facilitators and participants in Issue Evaluation or Risk Reduction analyses, though much of the information may be useful to those preparing Comprehensive Facility Review level risk analyses.

A. Meeting Agenda

As with nearly all meetings, an agenda for the risk analysis meeting should be developed. It should be developed jointly by the team leader and facilitator(s) in advance of the actual meeting and sent to all participants. The agenda should be detailed enough to serve several functions as follows:

- To give a broad overview of the actual meeting to help members understand the issues to be discussed

- To structure the meeting to help achieve a time frame for the topics (the agenda should include a timetable for each major discussion)

- To provide information to those who will be attending on a part time basis when their input will be necessary (i.e. load specialists, response specialists, consequence specialists, etc.)

While most of the typical agenda items are discussed in other sections of this document, some particular sections of the agenda deserve further explanation and are as follows:

1. Introduction. - When a team is first assembled for a risk analysis, it is imperative that all members be quickly brought to an enhanced understanding of technical and operational issues associated with the dam. While this objective can be partially met through disseminating background information prior to the team meeting, schedules do not always allow for everyone to arrive at the meeting fully knowledgeable of the information provided. This part of the meeting is extremely important as a time for becoming familiar with the dam, the risk analysis process, and other team members. Even though some of the topics might seem trivial, obtaining early participation by all members is just as important as the information to be conveyed. If members of the group can become comfortable participating in this part of the meeting, they will more freely share their insights as the discussions become more technical. Suggested topics to include in this part of the meeting include:

- Client Expectations - Study objectives which have been agreed upon with the client should be shared with the team members for the purposes of making client satisfaction a team goal and for identifying any obstacles to meeting the client's expectations. It is often worthwhile to have the client attend this portion of the meeting so that any obstacles can be resolved quickly thus allowing the team to quickly focus in on their task.

- Team Members - Each team member should be asked to introduce themselves with more than the customary background information. Information about each team member's previous experience with the dam and with risk analyses in general will help all to better understand the resources available to the team as a whole. Each team member should also be encouraged to express any expectations that they have about the process including areas that they believe need to be investigated or even aspects of the dam that they intuitively believe to be high risk. As the meeting goes on, it will be important to be able to address the individual needs and expectations of the team members in order for them to constructively contribute to the risk analysis process.

- Risk Analysis Process - A brief overview of the risk analysis process should be provided with special emphasis on the importance of the knowledge and judgement of each of the participants. Although some participants may have previous experience performing risk analyses, there may be some minor changes to the approach which are particular to the dam being considered. The follow-on use of the analysis results by the decision makers (i.e. risk assessment process) should also be explained.

2. Make Report Writing Assignments. - One person is responsible for pulling a final risk analysis report together. In most cases this will be the Team Leader. Others can be assigned responsibility for portions of the report, but the Team Leader will typically be required to compile and generate the final product. A person will still need to serve in the role of Recorder. This person captures the details of discussion as the risk analysis progresses. Team Leaders will most often not be the Recorder since they are required to participate intimately in the risk analysis process and would not be able to perform the duties of Team Leader and Recorder simultaneously.

3. Reviews. - An introduction to the dam and its appurtenant structures will help participants to understand the physical features and operational aspects of the dam. Summaries of identified dam safety concerns, previous analysis, data collection programs, and past performance will help the team members to frame their input during subsequent parts of the meeting. This can take up to several hours for a typical Issue Evaluation risk analysis.

4. Potential Failure Modes. - A potential failure mode is an existing inadequacy or defect originating from a natural foundation condition, the dam or appurtenant structures design, the construction, the materials incorporated, the operations and maintenance, or aging process, which can lead to an uncontrolled release of the reservoir. The participants should go through a discussion of all potential failure modes, and develop a thorough understanding of any failure mode, and screen out failure modes that are judged to be inappropriate or unrealistic.

5. Loss of Life Estimates and Other Consequences from Dam Failure. - All loss of life information, including population at risk, potential warning times and evacuation processes are discussed. In addition, Region, Area and Project personnel are queried directly about knowledge they possess regarding potential for loss of life. This helps ensure that loss of life estimates are characterized to the best degree possible for use in the risk analysis. Economic, social, environmental, and cultural consequences should also be discussed so that all risk analysis participants are aware of the broad spectrum of possible consequences associated with dam failure.

6. Risk Analysis Calculations. - The Facilitator(s) should briefly discuss how probability estimates will be solicited from participants and how this information will be used in calculations of risk. This should include how uncertainty will be portrayed and how the @Risk Software utilizes this information.

7. Conclusions. - When the probability estimates are completed and the event tree has been calculated, the team should discuss the results. Sometimes, where there is statistical information on the failure mode being reviewed, the team may consider how their results compare to the known failure rates. Most importantly the team should be considering whether or not the results seem to make sense in terms of their understanding of the known conditions at the dam. If there seem to be discrepancies, a review of the logic and probability estimates that have been prepared may provide a better understanding or identify a need to reevaluate the estimates. Facilitators serve a key role in ensuring that riak has been properly characterized in a fashion useable by the decision makers.

When the results appear reasonable to the team members, it is frequently beneficial for the team to develop a summary of their findings. Six questions have been developed as a means of addressing key areas of the summary. The questions are:

- Which failure modes contribute the greatest risk?
- What uncertainties enter into the estimates of risk?
- What information could be generated to reduce the uncertainty?
- What outcomes could reasonably be expected to result from collecting the information?
- How would the risk be affected by each of these outcomes?
- What are reasonable options/courses of action and what will they cost ?

Depending on the level of the analysis, answering these questions (as applicable) should provide valuable information to the risk assessment process.

8. Future schedules. - It is important for the team to understand the anticipated schedule to be followed after the meeting. While schedules for report completion will typically be determined at the time the project plan is developed, team members should freely discuss their commitment to the schedule. In addition, there may be a need to brief other portions of the organization and the team members need to be made aware of these briefings.

B. Developing Event Trees

1. Principles. - Event trees are used to represent sequences or progressions of events that could result in adverse consequences when a dam or associated structure responds to various loading conditions. By providing a graphical representation of the logic structure for the progression of each failure mode, an event tree becomes the template for subsequent assignment of event probabilities and calculation of risk. The event tree is also a tool for evaluating changes in risk given certain actions and assumptions. In addition, it is a means for identifying where the greatest potential risks are. And perhaps most importantly, it fosters common knowledge and understanding of failure modes, and synergetic discussion of various issues associated with failure modes. The risk associated with one sequence in the event tree is the product of the load probability, the structural response (failure) probability given that the load has occurred, the adverse consequence given that the load and failure have both occurred, and the magnitude of that consequence. The total risk for the load category is the sum of the products for all event tree paths.

An event tree consists of a series of linked nodes and branches. Each node represents an uncertain event or condition. Each branch represents one possible outcome of the event or one possible state that a condition may assume. Together, all of the branches emanating from a node should represent the mutually exclusive and collectively exhaustive set of possible outcomes or states (this is typically not done in the load range branches). The branches are mutually exclusive if each branch unambiguously describes one and only one possible outcome (i.e. there is no “overlap” among them), and they are collectively exhaustive if together they describe all possible outcomes (i.e. probabilities add up to 1.0).

The event tree is constructed from left to right, starting with some initiator event and proceeding through events describing the response of the dam to each level of the initiator. These event sequences are developed all the way to breach of the dam, and finally to consequences that result. Each event node is predicated on the occurrence of all directly-linked branches that precede it in the tree.

The best way to start creating an event tree is to establish failure modes through a failure mode screening process. Once a failure mode has been identified, the event tree should be formulated to show the sequence of events and/or conditions which would have to take place or exist in order for the dam to respond in an adverse manner. Often it is useful to begin with "logic diagrams" that generally list the various sequential steps needed to take place during a given failure mode. These diagrams are less complex than the formally constructed event trees. The event tree should also identify possible interventions which could terminate the development of the adverse consequence. An example of this might be consideration of construction of an alternative(s) that would prevent the continued development of adverse consequences. For instance - have an "intervention" node in an event tree for a seepage related failure mode where the probability of successfully constructing say filters, or drains, or a berm, etc., is considered. Successful intervention would terminate one path of the event tree.

Performance Parameter Technical Memorandums (PPTMs) are particularly helpful for identifying failure modes. If a PPTM exists, the performance parameter team has already done most or all of the ground work by listing and describing failure modes along with monitoring that can help detect initiation of a failure sequence. The risk analysis participants should still try to identify additional failure modes, or, if necessary, revise the ones listed in the PPTM. If the risk analysis participants do discover something missing in the PPTM, they should recommend a revision to that document.

Case histories can provide additional insight for identifying failure modes and for breaking down the modes into sequences of events, a process sometimes called "failure mode decomposition". Failure and incident information provided in case history reports describe the progression and sequence of the events that have occurred for other dams. This information provides the means for conceptualizing and specifying the occurrences, conditions, and interventions that could be pertinent to the dam under consideration. For many dam types and applicable failure modes, there are often one or more especially well-documented failure(s) or incident(s) that chart the progression of events in some detail. Incidents that have progressed nearly to failure but have stopped for some reason provide information that is as valuable as information regarding complete failures.

The potential failure modes should be identified and each event in the progression should be explicitly and unambiguously documented (such that all team members have a common understanding of the potential failure modes) for later use in the structural response probability estimation phase. Considerable effort should be devoted to determining atypical failure modes that might be unique to the dam in question. The potential for adverse consequences associated with improper operation of the facilities should be considered as one of these unique failure modes.

2. Complexity. - The size and complexity of the event tree depend on what is known about the dam and its expected behavior under different loading conditions, on the complexity of the failure modes considered, on the number of load ranges needed, and to some degree on the purpose of the risk analysis. The event tree must balance needs for comprehensiveness and detail against needs for consistency, clarity, and communication. Too little detail can reduce the ability to target specific risk contributors and can create problems in making reasonable structural response probability estimates. Too much detail, and the event tree becomes unmanageable or incomprehensible to a degree that important insights are lost. Techniques for achieving an appropriate level of detail in the event trees include the following:

- Truncate non-failure branch pathways as early as possible - There is no need to propagate event sequences once it becomes apparent that they cannot lead to an uncontrolled release of the reservoir. The reasons why an event sequence branch is truncated are an important part of the risk analysis documentation.

- Construct separate event trees for each load type, and sometimes, for each load increment - These trees will often be similar or identical, but constructing them separately and sequentially better organizes the process.

- Use a staged approach - As with any other engineering analysis, it is unreasonable to expect that everything can be fully captured in an event tree on the first pass through the problem. A comparatively simple initial effort can identify the key elements in the tree that need to be expanded and less important parts that can be pruned in subsequent iterations.

- Limit the number of load increments for initiator events - Bounds for load increments should be chosen specifically to bracket load ranges where it is expected that the structural response (or the consequences of dam failure) will be fundamentally different from the structure's response (or the dam failure consequences) in other load ranges. Sometimes load ranges are selected to represent information available from related analyses. Dividing the full range of possible loading values into a few increments is usually sufficient for most problems. While any number of increments can be used, there must be sufficient reason to suspect that considering different load increments will lead to different structural responses or to some fundamental change in the adverse consequences.

3. Load Ranges and Increments. - The flood or earthquake initiator events can take on any value over very wide limits of the recurrence curve. It is necessary to confine these limits to a sensible range of values that can affect the structural response or consequences in a significant way. The number of increments and how they are defined have important implications on design of the event tree that affect its size and the ease with which subsequent structural response probabilities can be estimated. Two threshold load levels naturally suggest themselves: a threshold below which no structural damage or adverse consequences are expected, and a threshold above which structural failure is almost certain to happen. Between these thresholds is a load range where structural damage or adverse consequences is possible to varying degrees. Within this range other threshold load levels can be identified where significant changes in structural response or possible adverse consequences take place.

Often, the maximum load already experienced by the dam may be selected as the threshold below which no structural damage or adverse consequences are expected. The dam has survived this load, and one can usually assume that the dam will survive a repeat of this load, unless there is some progressive degradation mechanism at work. Parametric studies conducted as part of a previous dam safety analysis can also provide insight regarding this lower bound threshold. Examples of these approaches to developing load ranges are:

Hydrologic Loading - Using the flood of record to establish the threshold of adequate spillway performance. The spillway either successfully passed or did not pass the flood of record.

Seismic Loading - A comparison of available liquefaction susceptibility studies to potential earthquake induced peak horizontal accelerations at a dam site can be used to set the lower bound of earthquake shaking that a structure can withstand without failure of the structure, .i.e., the acceleration bound below which no liquefaction is expected to occur.

Static (normal) Loading - There may be a geologic feature located at an elevation within a reservoir storage area where inundation by water begins development of potentially adverse seepage conditions. Below the elevation of this geologic feature dam performance related to seepage is adequate. The time period the reservoir water surface is below the elevation of the geologic feature would be one bound on the static loading.

The lowest load range is very important due to its relatively high occurrence probability. This load range should establish the load range for which the dam is expected to perform without failure. Typically, this load range is called the "threshold" range for initiation of failure. Participants must be careful to assess the failure threshold value realistically. A "conservative" threshold estimate which underestimates the load level at which failure can occur will significantly increase the perceived risk at the dam.

Arbitrary designations such as the Probable Maximum Flood (PMF) or Maximum Credible Earthquake (MCE) generally should not be used as threshold levels. Deterministic analyses to create a PMF hydrograph and route the hydrograph through the dam's spillway and outlet works usually indicate the dam will overtop at some level well below the PMF. Likewise, some dams would not be able to withstand earthquake loading well below the MCE. Furthermore, it is difficult to accurately associate return frequencies with a PMF or MCE.

The resulting threshold levels, and the corresponding ranges between them, may initially be chosen inappropriately by the participants. The calculated risk for a particular event tree branch may appear intuitively incorrect. This particularly happens when the chosen ranges are too wide. Risk analysis participants typically estimate a high structural response probability for a given range that might be more correctly associated with just the upper end of the range. The lower end of range determines high frequency of load occurrence. When the selected probabilities are multiplied through the branch, the calculated risk appears too high. If the result does not make sense, the participants should try splitting the load range so the probability estimates more accurately reflect the anticipated performance of the dam.

C. Estimating Load Probabilities

The three categories of loading conditions typically required in risk analysis are static, hydrologic, and seismic. Each of these loading conditions is briefly described in the following paragraphs. The discussion emphasizes the products needed by the participants, the range of extrapolation, and the uncertainty of the structural response probability estimates. The technical details for developing the loads are not described, but may be found in numerous engineering textbooks and manuals. The responsibility for estimating load probabilities lies with the supporting technical specialists and the technical staff participating in the risk analysis.

Generally, load probabilities are estimated using the staged approach. The level of detail of the risk analysis determines the amount and quality of information used in the analysis. More detailed stages of risk analysis may require more detailed loading condition information. Additional work on the loading conditions is performed only if warranted by the value added to the dam safety decision process (through the reduction or better portrayal of uncertainty). Extra study cost should be weighed against the expected improvement in the quality of the dam safety decision.

The failure of upstream dams should not be considered as loading conditions in a risk analysis. The risk of multiple dam failures/incidents are addressed by assigning the cause of failure to the most upstream dam failure and including the resulting dam failures as consequences for that dam.

1. Static Loads. - The static loading condition encompasses a wide variety of specific loading conditions to which a dam is routinely exposed during the course of normal operation. These loads can include hydrostatic loads imposed by the reservoir, static and dynamic loads imposed by operating various components of the dam and its appurtenant structures, loads induced by landslides at the dam or on the reservoir rim, or by the hydraulic phenomena (seepage, erosion, cavitation) associated with water passing through and around the dam.

Most static loading conditions are related to the reservoir level either in terms of the magnitude of the load, time of exposure to the load, or the potential for adverse consequences. Therefore, historical reservoir elevation records are an important information source for assessing the likelihood of failure modes associated with static loading conditions. When evaluating the historical reservoir information, it is important to consider the data in a fashion which is consistent with the failure mode being developed. In the case of gates, the exposure is directly related to exposure time above a given reservoir water surface elevation. In the case of piping, the exposure may be more related to whether or not the reservoir has reached a specific level at some previous time. In each case, the historical data must be organized in a fashion which yields meaningful information for the anticipated potential failure mode.

For most team risk analyses it is likely that a Reservoir Load Frequency Curve will need to be developed by Reclamation's Structural Behavior and Instrumentation Group. In some cases information available on reservoir elevations is incomplete and additional information for development of a Reservoir Load Frequency Curve will need to be obtained through Region, Area or Project Offices. In addition, it will be necessary to evaluate what, if any, load ranges need to be considered when performing a given risk analysis (see additional discussion of load ranges in Section IV.B, "Developing Event Trees"). The load ranges may be discrete elevations of concern (i.e., there might be a geologic formation at a given elevation that relates specifically to a given failure mode) or there could be a continuous loading condition (i.e., the failure mode is seepage through the embankment/foundation contact when the reservoir fills each year and the structure responds quickly and fully saturates).

2. Hydrologic Loads. - The development of flood frequency relationships and reservoir inflow hydrographs are important inputs to the risk analysis process. For risk analysis, the focus of flood evaluations shifts from a single maximum event, like the probable maximum flood, to describing a range of plausible inflow flood events. The products developed for a particular risk analysis depend on the level of study and the information available. In some cases, concurrent hydrographs are needed for tributaries located downstream of study dams so that flow conditions can be defined for analysis of the consequences of flood induced failure modes. Likewise, for more detailed risk analyses, regional and site-specific hydrologic and paleoflood investigations may be necessary to determine the flood potential and frequency.

Following are several types of studies which may be performed to generate the necessary flood frequency information for a risk analysis. The risk analysis participants should evaluate the currently available flood routing and flood frequency information in conjunction with the flood hydrology technical specialists to determine what type of study, if any, is required.

- Preliminary Flood Frequency Analysis - The analysis will use available information including recorded stream flows, paleoflood data, regional envelope curves, rainfall frequency relationships, and historical accounts of large floods. This information will be combined and synthesized into a flood frequency relationship for peak inflow at the study dam. The curve will extend to floods with return periods in the range of the 1,000- to 10,000-year events and include an estimate of the associated uncertainty.

- Flood Hydrograph Analysis - This analysis builds on the information generated in the preliminary flood frequency analysis. Along with the updated flood frequency analysis, hydrographs will be generated and routed in an attempt to identify the effects of reservoir storage and flood volumes on downstream releases. Simplified approaches will be used to minimize the cost of the study effort.

- Detailed Flood Frequency Analysis - A combination of methods will be used to analyze the problem. The appropriate tools depend on the available information. Some of the tools available include detailed paleoflood investigations, design event-based precipitation-runoff modeling, stochastic event-based precipitation-runoff modeling, meteorological studies, atmospheric storm modeling, continuous simulation modeling, etc. Confidence in the results comes from combining appropriate methodologies.

3. Seismic Loads. - For utilization within a risk-based framework, seismic hazard evaluation must explicitly contain information on the frequency of occurrence (and/or exceedence) of relevant loading parameters. The currently accepted practice for evaluating and conveying seismic hazard information in this fashion is probabilistic seismic hazard assessment (PSHA). The first step in any seismic hazard evaluation is source characterization. For use in risk analyses, both fault and areal (background or random) sources should be incorporated into the hazard evaluation. PSHA attempts to incorporate uncertainty in source characterization by allowing for alternative source and recurrence models as well as uncertainty in recurrence parameters. For fault sources, uncertainty in source dimensions, sense of slip, and orientation (and hence maximum magnitude) should be incorporated for detailed studies. Definition of earthquake recurrence for both areal and fault sources should incorporate some estimate of the uncertainty in seismicity rate and the assumed magnitude/recurrence relationship. The ultimate goal of PSHA is specification of ground motions. For use in risk analysis, ground motion estimation should incorporate uncertainties in source-site distance, selection of attenuation relationships, and observed variability in ground motions (sigma) in the final product.

By definition, PSHA integrates contributions over the entire spectrum of magnitude and distance from each defined source and then sums contributions from each source to develop a distribution of ground motion level for each annual frequency of exceedence. The most frequently used seismic hazard product is a simple hazard curve that relates a ground motion parameter (often peak horizontal acceleration, PHA) to annual probability of exceedence. Because PSHA is integrative, this curve contains contributions from all sources, magnitudes and distances. The risk analysis team may find it useful to consider alternative representations of the hazard. Frequently used options include: breaking out contributing sources individually; portraying contributions by magnitude level; sorting the hazard into discrete magnitude and hazard "bins"; considering alternative ground motion parameters such as response spectrum ordinate(s), acceleration or velocity spectrum intensity, or Arias intensity.

For use in liquefaction evaluations, consideration of ground motions organized by magnitude levels is often quite useful. Risk contributions from the various magnitude levels are then summed. This allows for integration with commonly used geotechnical parameters (such as magnitude adjustment factor) when evaluating liquefaction likelihood. Likewise, acceleration spectrum intensities (ASI) is commonly used as input for the structural analysis of concrete dams, spillways, and outlet works intake towers when subjected to seismic loads. This information can then be used to estimate the probabilities of the various responses of the dam or appurtenant structures to the seismic loading conditions being evaluated.

D. Estimating Structural Response Probabilities

Estimating structural response probabilities is generally the most difficult and time-consuming activities faced by a risk analysis team. It is also probably the area of the whole process that might change most with time. Steve Vick has prepared an excellent summary of the factors, influences, and considerations that should be understood and incorporated into a risk analysis when undertaking this task. This information is provided in Appendix A.

Summarized below is a process for making structural response probability estimates that has been found to work well for various risk analyses. All steps described below are performed jointly by all the participants of the risk analysis team.

Step 1. - The first step is to be sure each team member has a clear understanding of each node of the event tree. (An event tree node represents a choice at which the preceding event must be considered to have happened and two or more subsequent events could take place.) This is best done by having the facilitator(s) write out the description of the node at the top of a flip chart (or some other visual means that is readily accessible at any time). An open discussion usually takes place during this step where team members freely discuss their understandings of the event node and the wording being proposed. The facilitator should then capture the thoughts of the group into the description of the node. For instance, a node description for “unfiltered exit” might be:

> “the soil particles that are being carried by seepage flow must exit from the dam at a location where there is no filter present to trap the soil. A filter is defined as a soil that reasonably meets Reclamation’s design standard for filters.”

It is perfectly acceptable to further decompose the node in the word description. For instance, a node description as above might also add:

> “The zone 2 of the embankment must reasonably meet filter criteria for the zone 1. The zone 3 outer shell must reasonably meet filter criteria for the zone 2"

Step 2. - The group then ‘brainstorms’ any and all information that is pertinent to the event node being discussed. Each piece of information is listed on the flip chart in either a ‘factors leading to a higher probability’ or ‘factors leading to a lower probability’ column depending on whether the information is can be used as evidence to support or oppose belief in the event. The listing is usually done on the same chart immediately below the node description. The terms ‘factors leading to a higher probability’ and ‘factors leading to a lower probability’ are used in terms of the event node, as described, actually happening. The team should agree that the information is being placed in the correct column. Disagreements are usually solved by using clear wording that describes the information or by adding an opposing view in the opposite column. The purpose of this step in the process is to display all the information that will be used in making the estimate for all team members to see and discuss. As described below in step 3, the team members can judge for themselves the importance of the information being listed as they make their estimates.

Nearly any type of information is permissible to be listed if it helps the team members make their estimates. For instance, “gradation limits in construction specification meet filter criteria for the zone 1" might be listed in the ‘factors leading to a lower probability ’ column for the ‘unfiltered exit' description discussed above in step 1. Others might be "93 out of 95 gradation tests of as-constructed earthfill showed acceptable limits were achieved" [factors leading to a lower probability]; "2 out of 95 gradation tests of as-constructed earthfill failed the limits and were left in place" [factors leading to a higher probability]; "the specified gradation is likely to segregate during placement" [factors leading to a higher probability].

Also to be listed are any similarities/dissimilarities with the case histories being used as a comparison. For instance, "the zone 2 for 'Dam X' (the case history dam) was much less compatible for the zone 1 than is the dam under study" [factors leading to a lower probability].

Even information of a general nature or member biases can be listed. For instance, one team member might want to list his/her concerns as to the appropriateness of the filter criteria used in the listing of the above information and include this in the 'factors leading to a higher probability ' column. An example showing a record of steps 1 and 2 is shown below. Considerable report-writing time can be saved if this chart can be created on a computer as the discussion takes place.

Record of Discussion for Probability Estimates

<table>
<tr><td>Dam Component:</td><td>Alternative: Reservoir Restricted to 238 ft.</td></tr>
<tr><td colspan="2">Failure Mode: 1a- Piping from embankment into foundation- Alluvial -
RESERVOIR RANGE 230-240</td></tr>
<tr><td colspan="2">Event: Unprotected exit -does not have ability to block particle movement (exit that has large open volume to store and/ or pass embankment materials such that a piping initiated breach of the structure would not be prevented)</td></tr>
<tr><th>Factors leading to higher probability</th><th>Factors leading to lower probability</th></tr>
<tr><td>Open work gravel seen in 2 test pits and 1 exposure</td><td>Alluvium appears to meet filter criteria for zone 1 & 2 embankment (based on sampling 50+-tests)</td></tr>
<tr><td>Sampling method used for Alluvium appears to meet filter criteria for zone 1 & 2 embankment (based on sampling 50+-tests) may not have gotten the fabric of the soils.</td><td>gravels are probably discontinuous with intervening finer grained materials</td></tr>
<tr><td>1 outlier of samples did not meet filter criteria.</td><td>Construction process (for emb) would have tended to mix some finer material into open gravels.</td></tr>
<tr><td>Original design probably did not account for filter criteria</td><td>High gradient across thin us blanket (even cracked) therefore no piping</td></tr>
<tr><td></td><td>Zone 2 from alluvial source</td></tr>
<tr><td></td><td>Discontinuity of material</td></tr>
<tr><td></td><td></td></tr>
<tr><td></td><td></td></tr>
</table>

Estimates:

Reasonable Low: ____________________

Reasonable High: ____________________

Distribution of estimates between reasonable low and reasonable high: ____________________

Step 3. - Once a clear understanding of what the node of the event tree represents has been established (step 1), and all relevant issues by team members related to that node have been aired and summarized (step 2), then a probability estimate may be made for the node of interest.

The team should obtain "reasonable high" and "reasonable low" probability estimates. Elicit a "reasonable low" probability estimate by selecting a trial value and asking "Is it unlikely that the actual probability value is less than this value?" Elicit a "reasonable high" estimate by selecting a trial value and asking "Is it likely that the actual probability is less than this value.

Determine if the group feels that any given value within the established range should be more likely than any other. Stated another way, does the group feel that all values within the range are equally likely? If there is no single "most reasonable" or "popular value", then a uniform distribution should be used. If there are reasons to suspect one value is more likely, these reasons should be stated for the record and a triangular distribution should be used with the peak of the triangle placed at the value which would be expected to occur most often. Related discussions on establishing estimate distributions are provided in section V.B.

The team should be told how the distributions will be used in the Monte Carlo analysis. The expected value for the both the uniform distribution and the triangular distribution will be the mean value of all the random selections for each variable during the simulation. For the uniform distribution this should not be a problem. However, if the group believes that an erroneous mean value is to be used about which the random simulation should pick values equally distributed, then the group might reconsider if a triangular distribution should be used.

The mean of the triangular distribution is often not the same as the mode. During the simulation, values will be equally distributed about the mean. The mode will be the value randomly selected more often than any other during the simulation, but the 50th percentile will often be some other value. If many of the distributions for events in the event tree are skewed like this, it may result in the "most popular" estimate calculated for annualized life loss being off-center within the range estimated from the Monte Carlo simulation. This is not a technical problem, but it may be difficult to communicate the reasons to those not well versed in probability and statistics.

Verbal descriptors can be used for assigning response probabilities when there is not a basis (i.e. appropriate statistical information) for use of what can be termed the "known" failure frequency rate method. For example, under these circumstances the team members can use the subjective information that was generated during step 2 ("factors leading to a higher probability " versus "factors leading to a lower probability " exercise) to judge if the event tree node designated "unfiltered exits" is more likely or unlikely relative to the scale of verbal descriptors as shown in the following table:

VERBAL DESCRIPTORS

Descriptor	Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

Background information related to the development of relationships between verbal descriptors and probability estimates can be found in Appendix A.

In the example being used, the team members might assign a verbal descriptor of "very unlikely" (probability of 0.01) to the node described as "unfiltered exit" in step 1 above based on the available information:

> "93 of 95 gradation tests of as-constructed zone 3 earthfill materials generally met Reclamation filter criteria for the zone 2 earthfill material where seepage might exit"
>
> "Zone 3 earthfill materials are such that they are not likely to separate and segregate during placement"
>
> "As-built drawings indicate that zone 2 and zone 3 earthfill materials were placed to the lines and grades specified"

Estimates of response probabilities can sometimes be made on a more quantitative basis by comparing known historical or statistical databases that are relevant to the node for which a response probability is being estimated. An example of this method for estimating a response probability for a node described as "unfiltered exit" might be:

> "Reclamation has about 150 dams that have clay tile drains"
>
> "22 of these clay tile drain systems have been shown to have defects or crushed zones that compromise the integrity of the drain"
>
> "While none of these 22 compromised clay tile drain systems have lead to failure of a Reclamation structure, there have been 6 incidences where material was piped through the compromised portions of the clay tile drain system, i.e., Clark Canyon Dam"

Based on the outlined information, one could assign an estimated response probability of 0.04 (6/150) for an "unfiltered exit" related to Reclamation dams with clay tile drain systems. The statistical information presented here for drains and piping incidents is only hypothetical, but this type of information could be gathered in many cases to help make probability estimates. Any available statistical information of this nature should be presented in establishing the likely ranges for the probability estimate.

Another useful way to incorporate performance based probability assessments is to consider certain repeated events or multiple examples of an identical condition as repeated Bernoulli trials. If a random event has a probability of occurrence of p, the probability that this event will occur in n independent trials, p_n, is given by the following equation:

$$p_n = 1 - (1 - p)^n$$

An example would be a pair of fair dice thrown 10 times. The probability of getting two sixes each time the dice are thrown is 1/36. The probability of getting the two sixes at least once in 10 throws is $1 - (1 - 1/36)^{10}$, or about 25 percent.

It is appropriate to consider this equation in two situations where structural response probabilities are being estimated. One situation is where a potential initiating event takes place many times over the life of a dam, and each time the event occurs there is the same probability that this event will trigger some other event. In this situation, p is the probability that the initiating event will trigger some other event, and n is the number of times the initiating event has occurred. Another situation is where many dams have the same component, and if this component is present, there is a certain probability it will cause some other event or condition to happen. In this situation, n is the number of dams and p is the probability the condition will cause the other event to happen.

One way this can be used is to check the reasonableness of a probability estimate. Assume a given reservoir has reached elevation 5340 fifteen times in the last forty years, and that no soil materials have appeared in seepage collection weirs during that time period. Assume that when the team is considering piping, the team members estimate the probability is .3 that material movement would begin should the reservoir reach elevation 5340 in any given year. The above equation says it is nearly certain (a 99.53 percent chance) that material movement should begin if the reservoir rises above 5340 fifteen times. Since the reservoir has been above that elevation fifteen times and no material has been observed, the .3 probability estimate would seem unreasonable (unless other factors could be placed in the "factors leading to a higher probability" evidence column).

Step 4. - The risk analysis participants then identify the factors from step 2 that had the greatest effect on the probability estimate generated in step 3. Returning to the flip chart containing the factors pertinent to the event, the team should identify those items on the flip chart which were most important in arriving at the probability estimates. In addition, the team should indicate why it believes the most significant factors should receive more weight than others. This can include a discussion of what adverse situations actually exist versus what adverse situations only have the potential to occur. While this process may result in debate among the participants, this discussion can bring out additional information which was not previously available or readily understood. This information and discussion should be documented by the recorder.

Step 5. - The facilitator(s) should ensure the risk analysis participants have reached consensus on the probability and uncertainty estimates. **This does not mean that the facilitator(s) must force all members to accept a single estimate.** Rather, the facilitator(s) must sense the group's feeling as discussion takes place, suggest a reasonable starting place as a best estimate, and canvass the group's willingness to accept the estimate. The facilitator(s) may use words like "I'm sensing the group feels fairly neutral about this estimate, how about 0.5?" Or, "I sense there are more reasons to believe we are on the likely rather than the unlikely side of being neutral." If the discussion indicates the event is not very probable, the facilitator(s) could use the verbal descriptors by suggesting: "I sense the group feels this event is not very likely, should this be very unlikely or virtually impossible?"

If the group cannot agree on an estimate, the divergent opinions must be accounted for in the analysis. At this point, the facilitator(s) should focus more on getting agreement on the possible range and characteristic probability distribution for the estimate (see Section V). The facilitator(s) should lead the discussion between the protagonists of the opposing views and identify the underlying premises or key evidence supporting each argument. This is a very fruitful area to obtain ideas that would suggest further exploration or analysis to resolve the differences. The use of the software "Precision Tree" and "@Risk" makes it very easy to carry a range or different distributions through the risk analysis calculations, and to examine "what if" scenarios to determine how a given piece of information might affect the outcome.

If the group cannot agree that a range or distribution will adequately characterize their judgement, then the analysis can be conducted using each representative estimate in separate calculations. The separate calculations for risk would then be reported along with the descriptions of the conflicting ways the group members saw the problem.

Step 6. - Once consensus is reached on the specific response probability estimate and uncertainty, the process continues by repeating steps 1 through 5 for each remaining node of the event tree.

When steps 1 through 6 have been completed for all the event nodes, the risk analysis process continues by considering and quantifying what adverse consequences could occur, as described in the following section.

E. Estimating Consequences

Potential consequences resulting from an uncontrolled release of a reservoir have several different dimensions. In addition to the economic losses related to lost project benefits and potential damage to property in the inundated area, there is the potential for loss of life, alteration of the habitat and environment, social impacts on the local community, and loss of confidence in the dam owner and operators. Since these consequences are not directly commensurable, the weights given to each for decision making are generally made separately from the technical analysis. The process of weighing different values in decision making is called risk assessment, as opposed to risk analysis. However, certain technical data is required by the decision makers to understand the magnitudes of the various dimensions of the consequences. The following sections provide general considerations for estimating the potential magnitudes of uncontrolled outflows, the extent of the inundated area, and the resulting potential for loss of life and economic damages.

1. Dam breach parameters. - The breach parameters identified for each failure mode, especially the time for a breach to form, greatly affect the downstream flow rate from dam failure and the time available to warn the downstream population. Breach parameters assumed to develop inundation maps for Emergency Action Plans are generally conservative. During an Issue Evaluation risk analysis, it may be important to examine these assumptions. This is specially true if the reservoir storage is small and if a significant portion of the reservoir is released as the breach forms.

Breach formation parameters in embankment dams depend primarily on the amount of water in the reservoir, the hydraulic height, the methods of the dam's design and construction, and the type of failure. Empirical methods are used to determine the width, side slope angle, and the bottom elevation, and the breach development time [5,6,7,8,9]. Breach parameters can vary in a given dam depending on embankment height and foundation geology. The time for full breach development can depend on failure type. For example, a flow slide in an earthquake will result in immediate overtopping of severely disturbed embankment materials, whereas overtopping during a flood encounters intact materials. The breach development time can also vary according to the erosion resistance of the embankment materials and the degree of overtopping.

Breach development in concrete dams depends on the bedrock conditions (rock quality and jointing), the dam jointing and block size, and the type of dam. Breach development time for seismic loading might be sudden whereas the breach development time for hydrologic loading might take more time. In the case of gravity dams, individual blocks of the dam are capable of resisting reservoir loads without the support of adjacent blocks, which provides for the possibility of only a partial breach of a dam. However, arch dams depend upon the support of adjacent blocks to transfer loads to the foundation. If one block is removed, there is generally inadequate support for adjacent blocks.

2. Determining Inundated Areas. - A computer program, such as DAMBRK, is typically used to calculate peak outflows, flood routing parameters, and downstream inundation. Inundation maps contained in the SOP can generally be used as a conservative estimate for most risk analyses. Dambreak analyses for the SOP have traditionally been conducted assuming PMF level flooding. If life loss situations from lesser flooding, or from sunny day failure modes are found to be significant contributors to risk, there may be justification to recommend additional dambreak analyses. In areas where river confluence effects are significant, or where several stream courses inundate a given area, a two-dimensional program such as UNET can be used. More detailed guidance regarding flood inundation studies can be found in *Policy and Procedures for Dam Safety Decision Making* (Section II).

3. Warning time. - The time before a warning is issued can be broken down into a detection period, a decision period, a notification period, and a implementation period. After an event that initiates dam failure, time can pass before operations personnel detect a potential problem at the dam. This is the detection period. The decision period comes after the situation is observed, when outside expertise and decision makers may be consulted, and a decision is made that the situation will lead to a dam failure. Once this decision is made, the notification period follows during which the proper emergency response authorities are contacted and convinced that an evacuation is appropriate. Once the proper authorities have been notified, the warning may take time to reach those who must evacuate.

The time between the initiation of a dam failure and the issuance of a notice to evacuate a population, added to the time it takes for the flood wave to travel to the population, is the warning time. An upper limit to warning time assumes someone is at the dam to notice the failure, that this someone can make the decision that the dam is failing and that people should evacuate, that authorities are available and can be contacted to initiate evacuation, and that there is an effective way to notify the population at risk. To the degree that any of the above warning time components are missing or do not function properly, warning time is reduced accordingly.

The components of warning time are dependent on physical as well as human factors. The physical factors may be functions of the event time (hour, weekday, season) and the conditions after the event (e.g. extent of damage to infrastructure, evacuation routes, or communications).

The human factors include reluctance to issue an evacuation warning and degree of emergency preparedness.

Note that the empirical formulas correlating life loss to population at risk and warning time are based on many different warning scenarios. In most cases, warning actually came through unofficial channels. Someone notices higher than normal stream channel flows and the word starts to spread.

The risk analysis team should consider worst case and best case scenarios for each failure mode investigated to determine a representative range of warning times. The risk analysis team should consult with regional and/or area office staff familiar with the local state of emergency preparedness when discussing these scenarios.

4. Potential for loss of life. - Wayne Graham has provided a simplified procedure where much of the following is considered. If a more rigorous risk analysis is being performed, for each load case/failure mode for which loss of life is possible, the following procedure should be followed:

- Determine if there are seasonal changes to habitation or facility usage below the dam (or consider some other time period(s) that will reflect different uses of the flood plain). If there are significant differences in the number of people at risk from one time period to the next, assign probability estimates to the chance that the dam will fail within each time period by proportioning the number of days in these time periods to the number of days in a year.

- Estimate the probability that the dam failure will occur during daylight, during night when people are usually awake, during night when people are usually asleep.

- Estimate the number of people at risk. Sometimes the number of people at risk can vary significantly even after the seasonal and time of day determination has been made. For example, there may a campground that has 100 campers on Friday and Saturday nights and only 10 people the other 5 nights. In this case, the population at risk should be 100 with a probability of .29 and 10 people with a probability of .71. Select the number of categories to minimize the computational effort, yet still display the varying usage of the flood plain.

- Estimate potential for loss of life. Estimates of the potential loss of life are then based on the empirical data for lives lost in historic dam failures which has been gathered by Wayne Graham [10]. The best estimate for warning time, and the range of possible values for warning time should be carried through the analysis.

5. Evaluate economic losses. - ACER TM #7 [10] sets forth the procedures typically used by Reclamation to assess the risk for economic losses.

V. Documentation and Presentation

A. Event Tree Computations and Review

Risk is computed by finding the product of probabilities and consequences for each path in the event tree.

$$Risk = \begin{bmatrix} Probability \\ of \\ Load \end{bmatrix} \; x \; \begin{bmatrix} Probability \\ of\ Adverse \\ Response \\ Given \\ Load \end{bmatrix} \; x \;\; Consequences\ Given\ Response$$

By summing the values from all paths, the total risk can be determined. It is usually assumed in these computations that the outcomes for each event are mutually exclusive (i.e. there is no chance of combinations of more than one outcome) such that the risk can be computed by summing the individual pathway risk values. While the events are not always mutually exclusive, their probabilities in a dam safety context are generally small and the resulting joint probabilities have little impact on the accuracy of the computations. When the summed failure probabilities (non-mutually exclusive) from an event exceed 0.3, the outcome probabilities should be adjusted as shown in the example below.

Spreadsheets and decision analysis software provide for rapid reduction of the vast quantity of numbers generated during a risk analysis. One such combination is Microsoft Excel with the Decision Suite addin programs from Palisade Corporation. The Precision Tree portion of the addin provides the graphics and computations associated with an event tree while allowing the individual input values to be entered either manually or based on computations from other cells in the spreadsheet. The consensus estimates of the reasonable low and reasonable high values by risk analysis participants should be used to record estimated distributions of parameters in the spreadsheet. While the spreadsheet offers great flexibility in structuring the computations, it also carries with it significant risk of errors in the equations if they are not carefully crafted and copied from one cell to another. Some checks that can be performed to help ensure accuracy include:

- Entry of the event tree and values during the meeting of the risk analysis participants using a projector so that the participants can observe the tree and spot any data entry or logic errors as the event tree is being developed.

- Summing the probabilities for each set of branches from a single node in the tree to ensure that the probabilities sum to 1.0.

- Checking equations for linkages to the proper cells when event tree values are computed from other data in the spreadsheet.

- Review of the computed risk and/or probability estimates by participants to ensure that these values reflect their common judgement.

While conducting the risk analysis, there are often changes that are made to the event tree. Tree branches with no reasonable probability of occurrence and non-failure paths are truncated from the tree. Additional failure modes or additional detail to existing modes are added to the tree. In some cases a failure mode may be identified which will clearly not impact decision making based on the unlikelihood a number of events occurring in sequence. In these cases, it is acceptable to simply document the reasons why the failure probability is negligible without making specific probability estimates. Prior to finalizing computations, the structure of the event tree should be reviewed to ensure that it is consistent with the team's interpretation of the potential risks posed by the dam.

The final check of the spreadsheet should be a review of the risk results by the team members to ensure that the results reflect the collective judgement of the participants. Following the team meeting, many team members will have an intuitive feel for the greatest risks to the dam. If the computed risks show differently, this is an indication that the estimates and equations along the subject path need to be reevaluated to ensure their accuracy. Whether the discrepancy is due to error or lack of understanding of an event/response, this is an important part of the team developing a consensus that the risk values portray a reasonable estimate of the risk at that dam.

Example

In some cases, an event can lead to multiple possible outcomes which each have a relatively high probability. Consider the case of a hypothetical concrete arch dam. Participants in a risk analysis have determined that the dam could potentially fail by three different means following the occurrence of a large earthquake. The identified potential responses of the dam to a large ground motion were as follows:

Outcome	Failure Probability
A) Structural Failure of the Arch Dam	0.7
B) Failure of a Foundation Block on the Abutment	0.5
C) Failure of the Thrust Block	0.5

These three potential outcomes are not mutually exclusive since any one or a combination of the three outcomes could occur. Therefore, the probabilities must be adjusted to ensure that the sum of the probabilities of all possible outcomes equals 1.0. It can be assumed that the probabilities are statistically independent since the occurrence of one failure mode would not impact the estimates for the probability of occurrence of the other failure modes.

Step 1: Compute the probability of no failure occurring

This is best done using the following diagram to visualize the relationships of the probabilities (see Figure 4).

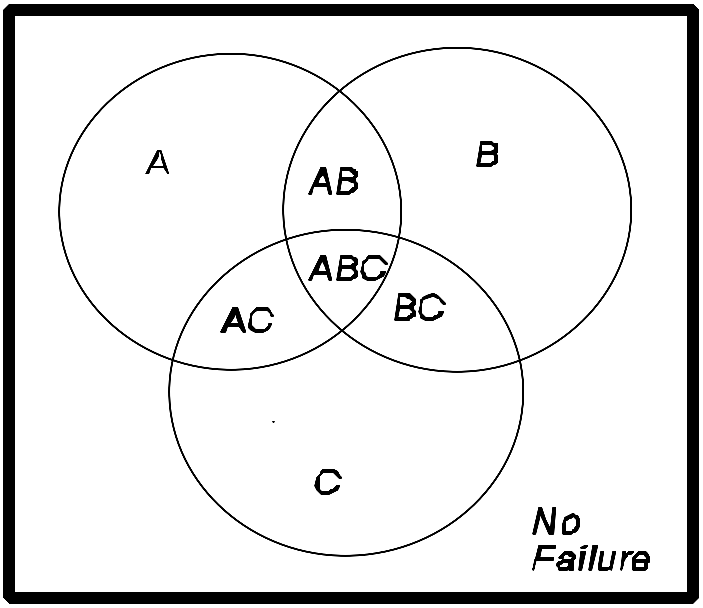


Figure 4

P[No Failure] (probability of no failure) = (1 - P[A]) x (1 - P[B]) x (1 - P[C])

= (1 - .7) x (1 - .5) x (1 - .5)

= (.3 x .5 x .5) = 0.075

Step 2. - Allocate a failure probability of (1- .075) = .925 among the failure modes.

The failure probability adjustment can be accomplished by normalizing the failure mode probabilities on the basis of the original estimates, or by allowing the team to estimate a new set of probabilities which sum to 0.925. Assuming that the original probabilities were estimated relative to one another, the normalizing procedure is preferable. Using the normalizing procedure, the adjusted probabilities for outcomes A, B, and C are:

P[A] = (.925/1.7) * .7 = 0.381
P[B] = (.925/1.7) * .5 = 0.272
P[C] = (.925/1.7) * .5 = 0.272

B. Uncertainty Analysis

When a value of risk or a probability of failure is computed, it is important to also characterize the uncertainty associated with those values. There are two characteristics of event tree input parameters which lead to uncertainty in the computed results.

The first characteristic is the natural variability of an input parameter as it occurs in nature. An example would be the reservoir water surface elevation behind a dam. While there may be a general pattern exhibited, there is a certain amount of variability due to variation in inflows and demands. This variability leads to uncertainty about the risk posed by a dam since a dam with a very low reservoir elevation has much less chance of uncontrolled release than a dam with a full reservoir.

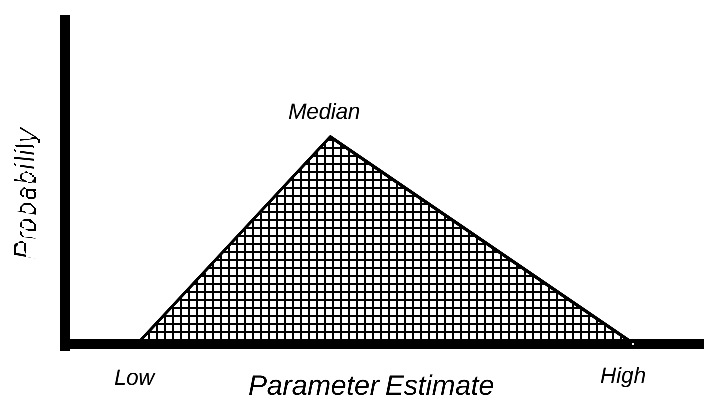
A second characteristic which leads to uncertainty in the results is a lack of knowledge about a particular process or mechanism represented by an input parameter. This type of uncertainty in the results acknowledges that the values of input parameters can be different from those estimated which would alter the results. This type of uncertainty can result from using idealized models to simulate complex processes, lack of understanding of natural processes, or the inability to obtain desired information.

Both types of uncertainty in the results should be evaluated simultaneously using a Monte Carlo Simulation process to combine the variations in and lack of knowledge about various input parameters. In a Monte Carlo process, the values of the input parameters are randomly generated based on each parameter's assigned distribution and the resulting risk and/or probability of failure is computed. When repeated many times, the results of the trials form a distribution for the expected values of the output (risk or probability of failure). It is recommended that the criterion for stopping the simulation be based on the output distribution statistics changing less than 1% in the last 100 iterations.

Input parameters can take on many types of distributions. When the team is estimating the event tree branch probabilities, they should also reach consensus on one of the following means of representing the input parameter:

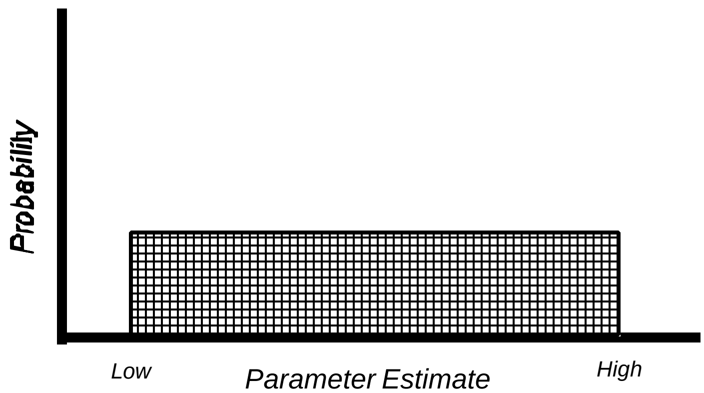
- Point Estimate - Point estimates are used when the probability estimates on the event trees are known, the team agrees that a single value is appropriate, or there is no reason to believe the estimates could vary significantly. Point estimates are also acceptable for preliminary risk analyses where the objective is to determine the relative magnitude of the risks.

- Triangular Distribution - A triangular distribution is used to represent a range of possible values in which the central values in the range are believed to have a greater chance of occurring or being the correct estimates. This distribution allows the effects of outlying estimates to be considered while placing primary emphasis on the consensus best estimate from the participants. The participants should develop consensus estimates of the reasonable low and reasonable high values which could be expected (see Step 3 in Section IV.D).



Triangular Distribution

- Uniform Distribution - A uniform distribution is used to represent a range of possible values in which all values are believed to have a equal chance of occurring or being the correct estimates. This distribution places placing primary emphasis on the extremes which define the range of possible estimates from the participants. The participants should develop consensus estimates of the reasonable low and reasonable high values which could be expected (see Step 3 in Section IV.D).



Uniform Distribution

While other distributions may appear justified for a particular parameter, the representations above provide a level of accuracy commensurate with the data generally available for performing the risk analysis. If the participants feel strongly that another distribution is justified, the purpose for its use should be documented.

The Monte Carlo analysis can be performed directly on event trees constructed with the Precision Tree software package using another component of the software called @RISK. Key steps of the Monte Carlo analysis include:

- Defining the output variables for which distributions are desired
- Defining the input variables to be estimated by distributions (distribution functions should already exist in those cells)
- Setting the simulation parameters to calculate expected values of the tree on each pass
- Setting the convergence criteria
- Running the simulation
- Graphing the results

At the conclusion of the risk analysis there will be a variety of numeric values related to the risk, P(load) x P(response) x (consequences), associated with the static, seismic and hydrologic loading conditions. A group of experts, led by the facilitator(s), then must reach a consensus on a portrayal of the risk associated with the various loading conditions considering any and all available information.

C. Report Preparation

Documentation of a risk analysis serves two principal purposes. One purpose is to provide a record of the risk analysis thought processes, assumptions, and estimates which influenced the outcome of the risk analysis, and what information would be of use to future investigations of the safety of the dam. Another purpose is to provide decision makers with sufficient information to allow them to incorporate risk based information into the decision making process for deciding whether or not to take action and what action to take. The objective of the documentation is to meet these goals with a reasonable level of effort.

To accomplish the above purposes, this section provides a suggested general framework for the documentation. The format is provided simply as a guideline to help the team identify information which would be appropriate to include. Each risk analysis will likely have its own unique circumstances which must be documented, therefore the emphasis in this section is on a general arrangement of information for the benefit of decision makers and future investigators. Documentation for both baseline and risk reduction type risk analyses will generally follow the format outlined below in the "Suggested Topics for a Risk Analysis Report."

One of the most important areas to document is that of the assumptions and/or exclusions made during the various stages of the risk analysis. The decision by members of the team to assume various values or to exclude some conditions can significantly alter the reported risk. This information should be identified for decision makers to ensure there is a common understanding of the risk analysis results.

1. Suggested Topics for a Risk Analysis Report - While the conditions and the associated risks at each dam are unique, there are similarities in the information needs of the decision makers. The following topics should be considered for inclusion into the documentation of a risk analysis:

- Participants - This section should identify the personnel who participated in the risk analysis and identify the roles that they filled.

- Scope - This section should include a summary of the purpose of the risk analysis, what are the problems and issues being addressed, and the depth of analysis performed to support the estimates and judgements made in the process. If any unusual processes were employed, they should be described here.

- Description of Facilities - This section should contain a brief description of the dam and its appurtenant structures to familiarize the reader with the facilities for which the risk is being analyzed. If the risk analysis is for the purpose of evaluating risk reduction alternatives, a brief description of each alternative should also be provided.

- Failure Modes - This section should summarize the ways in which the dam could reasonably be expected to fail. Each failure mode should described in sufficient detail to demonstrate how the failure mode would develop starting from the initiating conditions or event and leading to the uncontrolled release of the reservoir.

- Descriptions of Loads and Responses - This section should describe the static, hydrologic, and seismic loading conditions to which the dam is subjected. The information provided should include:
  - load ranges selected and the reasoning for selecting those ranges
  - probabilities of the selected load ranges (or a reference to their origin)
  - responses to the loading conditions
  - key factors at the dam which lead to increased or decreased estimates of the failure probability of the dam

- estimated consequences if the failure mode were to occur (include information on population at risk, breach parameters, and warning time estimates)
- uncertainties associated with the failure mode or the data used for making the probability estimates

- Summary/Conclusions/Recommendations - This section should include a summary of the key findings and essential information generated from the risk analysis process and address the following questions:

  Which failure modes and loading conditions contribute the greatest risk?
  What uncertainties enter into the estimates of risk?
  What information could be generated to reduce the uncertainty?
  What outcomes could reasonably be expected to result from collecting the information?
  How would the risk be affected by each of these outcomes?
  What are reasonable options for future action and what will they cost?

  These questions will help to focus the team on credible information which will assist decision makers in determining future actions to be taken.

  The final documentation should present results and reasonable options for action for consideration by the decision makers. Decisions of future actions to be taken are more appropriately documented in separate documents prepared by or on the behalf of the decision makers.

  Note: - In some cases, it will become apparent that there are some low cost actions which could make immediate reductions in risk at the dam. Examples may include simple changes in operating procedures or maintenance practices which result in more reliable operations. Risk can also be reduced by exercising the emergency action plan or by helping operations personnel to understand the importance of the visual monitoring parameters in the performance parameters technical memorandum. Any such opportunities for low cost risk reduction should be brought to the attention of the decision makers promptly.

- Appendices - The attachments to the report of findings should include the following items:

  - A list of reference materials used for the risk analysis
  - Copies of the event trees developed
  - Copies of the flip chart information documenting the important factors in making the probability estimates
  - Any other information needed to convey an understanding of how the estimated risks were developed

2. Authorship - The team leader, or another person(s), designated prior to beginning the risk analysis and with Group Managers assistance, will be responsible for writing risk analysis reports. The facilitators can assist with identification of an appropriate author(s). The responsible author will request any necessary help (from within or outside the Team) to ensure that information is adequately recorded for future reference. Facilitators will work with the team during the risk analysis to capture as much of the information as possible in event trees, logic diagrams, “pros” and “cons” of estimate sheets, etc. Facilitators will also assist in identifying critical information that should be recorded for incorporation into the report.

3. Checking - The process for checking event tree inputs and outputs, tables and figures should be in place prior to beginning the risk analysis. Facilitators can assist the team leader in outlining this process and identifying resources (with Group Manager help). Checking should include verifying that all probability estimates, and their distributions, were entered correctly. Accuracy of tables and figures should be verified. In addition, construction of the event trees in the spreadsheets should be checked. The latter may be completed by different persons, since a limited number of people have experience with the software currently used.

4. Facilitators and Certification - Review and certification of the risk analysis will be performed by the facilitators. Facilitators will be involved in the report preparation until the product has been certified as final, but facilitators will not write the report. In most cases these reviews and certification will be in lieu of a review by Group Managers. In addition, the facilitators will work with the team, Group Managers and the Dam Safety Office to identify contentious or specific issues that may require special consideration before proceeding with risk analysis.

5. Signatures (and what they mean) -

- **Author's Signature** - This is the signature of the person or persons with primary responsibility for writing the risk analysis report. All team signatures, such as concurrence, are not required. However, signature of the document by the author(s) does signify that a draft document was provided to team members, and that they had an opportunity to comment on the draft. The author(s) signature also implies that comments were considered and that any critical issues or influencing factors were incorporated into the document.
- **Certification Signature** - Certification signatures will be those of the persons who co-facilitated the risk analysis. These signatures will signify that Reclamation methodology, processes, and requirements were followed. In addition, these signatures verify that qualifications of the persons making various probability estimates were appropriate. The purpose of endorsing qualifications is to reduce the potential for inappropriate estimates, or conflicts, arising from limited qualifications that result in total rejection of risk analysis findings during organizational reviews (such as DSAT). Certification signatures will also signify that the spirit of the risk analysis and team dynamics are represented by the document. In other words, that any divergent views, critical issues, or significant influencing factors have been captured. This is a check of the author's responsibility to fully capture and represent the team's thinking. Finally, certification will serve to document that load specialists input and feedback were solicited.

- **Checked Signature** - Checking signatures will verify that all probability estimates, inputs and outputs and their distributions, were entered correctly into event trees, and that any other calculations, figures or tables have been checked. This may include "back-of-the-envelope" calculations performed during the risk analysis but not documented other than in the report. In addition, the accuracy of computer spreadsheets should be checked. These checks are likely to be made by different persons thus requiring two signatures, since a limited number of people have experience with the software currently used.

6. Distribution of Draft and Final Decision Memos - Since concurrence signatures from team members are not required on TRA reports, draft and final decision memos should be provided to team members as they become available. This is done out of courtesy, to ensure that folks know how the input they provided was ultimately used by Reclamation, and to ensure that all team members are cognizant of project issues and decisions.

7. Project (Overall) Peer Reviewer Participation - Group Managers and Senior Technical Specialists (or any one qualified with substantial corporate knowledge) may want to schedule time to participate on key risk analyses, perhaps on those where the "stakes" are particularly high or where there is significant controversy/divergent views. This would help ensure that all pertinent information is brought to the table and considered. Involving senior staff in this manner, on an as needed basis, would assist facilitators and teams in ensuring a proper scope for the risk analyses.

The signature and certification process above does not imply that the individuals signing these documents are validating the numerical values produced during the team risk analysis. Nor does the signature process indicate TSC concurrence. Signing individuals are not shouldering the burden of making decisions for the TSC or Reclamation. The risk analysis document is only one part of many inputs that are required to make decisions related to dam safety. TSC organizational peer review will still occur as various projects proceed through appropriate milestones in the dam safety process. In addition, the forum of Dam Safety Advisory Team (DSAT) can be used by the Dam Safety Office to provide any critical feedback on the risk analysis. Decisions on dam safety issues will continue to be made by the Dam Safety Office, Region, and Area Office personnel.

References

[1] Public Law 95-578, The Reclamation Safety of Dams Act, November 2, 1978 (as amended by Public Law 98-404).

[2] "Policy and Procedures for Dam Safety Modification Decisionmaking", U.S. Bureau of Reclamation document, April 1989 (Interim Guidelines)

[3] "Guidelines for Achieving Public Protection in Dam Safety Decision Making", U.S. Bureau of Reclamation document, January 8, 1997 (Interim Guidelines)

[4] Reclamation Manual / Policy FAC P02, February 17, 1998

[5] MacDonald, T.C. and Langridge-Monopolis, J., "Breaching Characteristics of Dam Failures", ASCE Journal of Hydraulic Engineering, Volume 110, No. 5, May, 1984.

[6] Von Thun, J. L., and Gillette, D. G., "Guidance on Breach Parameters", unpublished internal memorandum, U. S. Bureau of Reclamation, Denver Technical Center, March, 1990.

[7] Wahl, T. L., "Prediction of Embankment Dam Breach Parameters: Literature Review and Needs Assessment (draft)", U. S. Bureau of Reclamation, Water Resources Research Laboratory, PAP-735, Denver, Colorado, 1996

[8] Susilo, K. J., Mineart, P. R., and MacDonald, T. C., "Does Selection of Published Dam Breach Parameters Ensure Reasonable Results?", Proceedings ASDSO Western Regional Conference, Oklahoma City, OK, May, 1997.

[9] Susilo, K. J., Mineart, P. R., and MacDonald, T. C., "Considerations When Selecting Parameters for Dam Breach Analyses", Proceedings ASDSO Annual Conference, Pittsburgh, Pennsylvania, September, 1997.

[10] U.S. Bureau of Reclamation, “Guidelines to Decision Analysis”, ACER Technical Memorandum No. 7, Denver, Colorado, 1986.